NEUTRINO OSCILLATIONS WITH ATMOSPHERIC NEUTRINOS IN JUNO

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on behalf of the JUNO collaboration

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XXI International Workshop on Neutrino Telescopes,
Sep 29th – October 3rd , 2025, Padova

INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Padova

JUNO

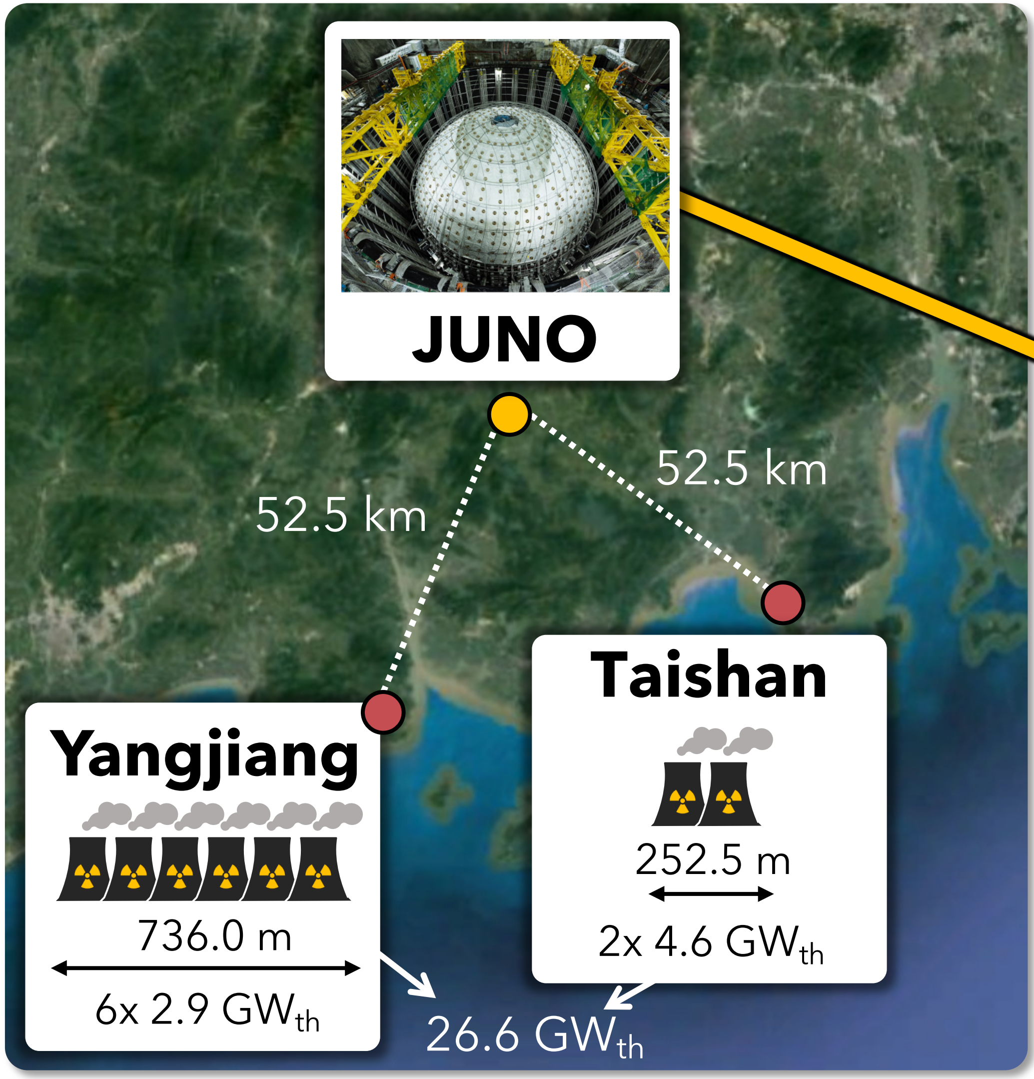
XXI Workshop on Neutrino Telescopes

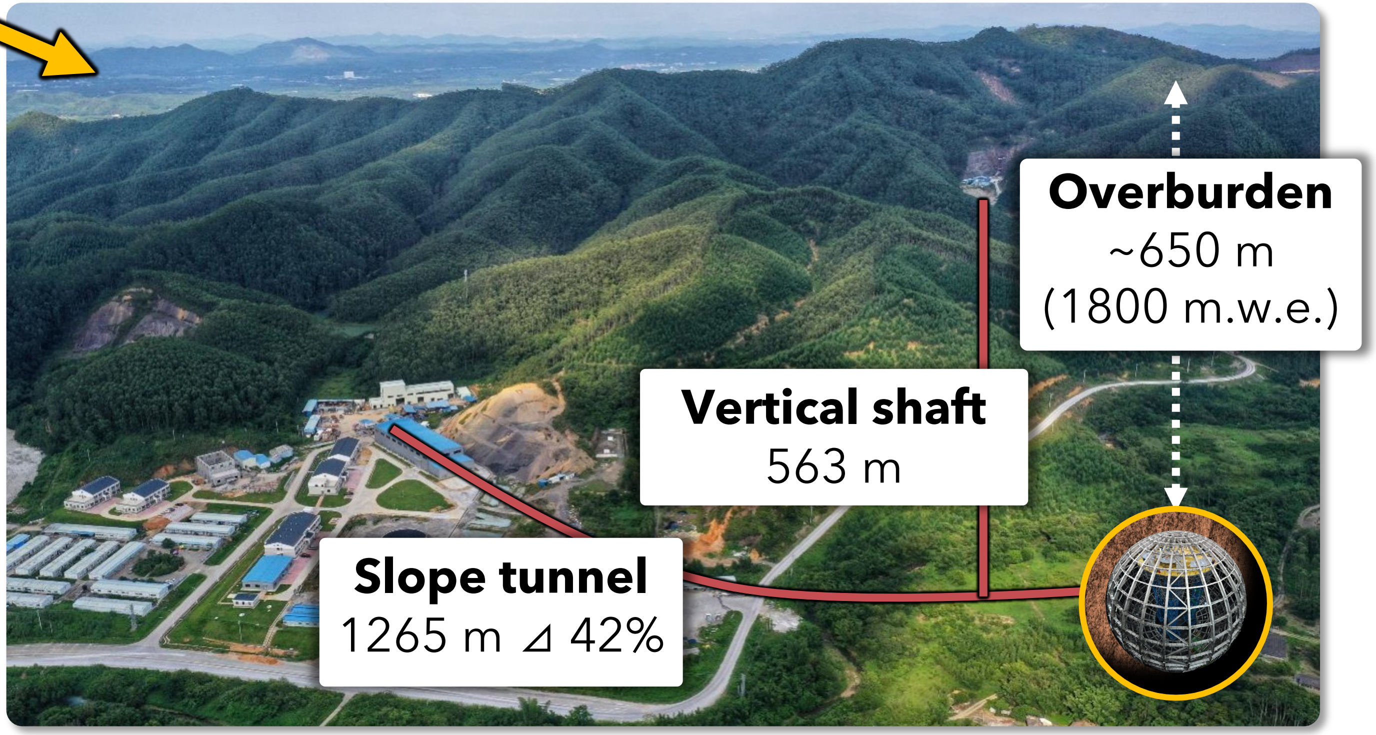
JUNO AT A GLANCE

PPNP 123 (2022): 103927

The **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**) is a **20 kton multi-purpose liquid scintillator detector**.

It sits at a baseline of about 52.5 km from eight nuclear reactors in the Guangdong Province of South China.





JUNO STATUS (2024 - TODAY)

Scheme from A. Garfagnini @ TAUP 2025

2024, Dec 18th
Start of Water Filling

2025, Jan
TT installation started

2025, Feb 1st
End of Water Filling

Water Phase

2025, Feb 8th
Start of LS Filling

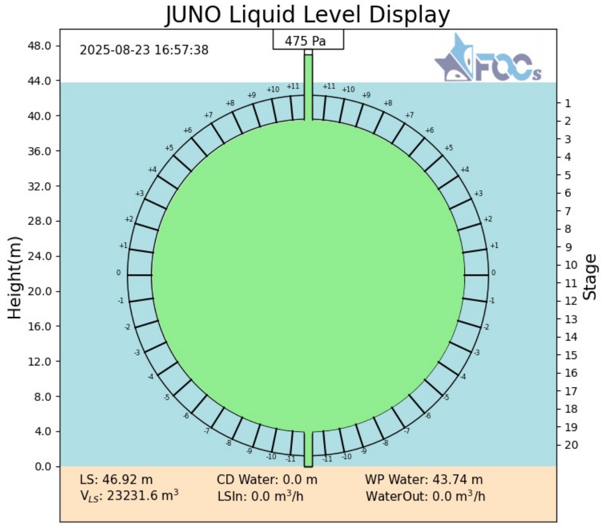
Mixed Phase

2025, June

2025, Aug 22nd
End of LS Filling

Full detector calibration

2025, Aug 26th
Start of Data Taking



JUNO KEY EXPERIMENTAL FEATURES

More details in M. Sisti talk

PPNP 123 (2022): 103927

Central detector (CD)

- ✶ **20 kton** of liquid scintillator
- ✶ **17612** 20″ large-PMTs and **25600** 3″ small-PMTs → **78% photo-coverage**
- ✶ Earth's magnetic field compensation coils

Water Cherenkov Detector (WCD)

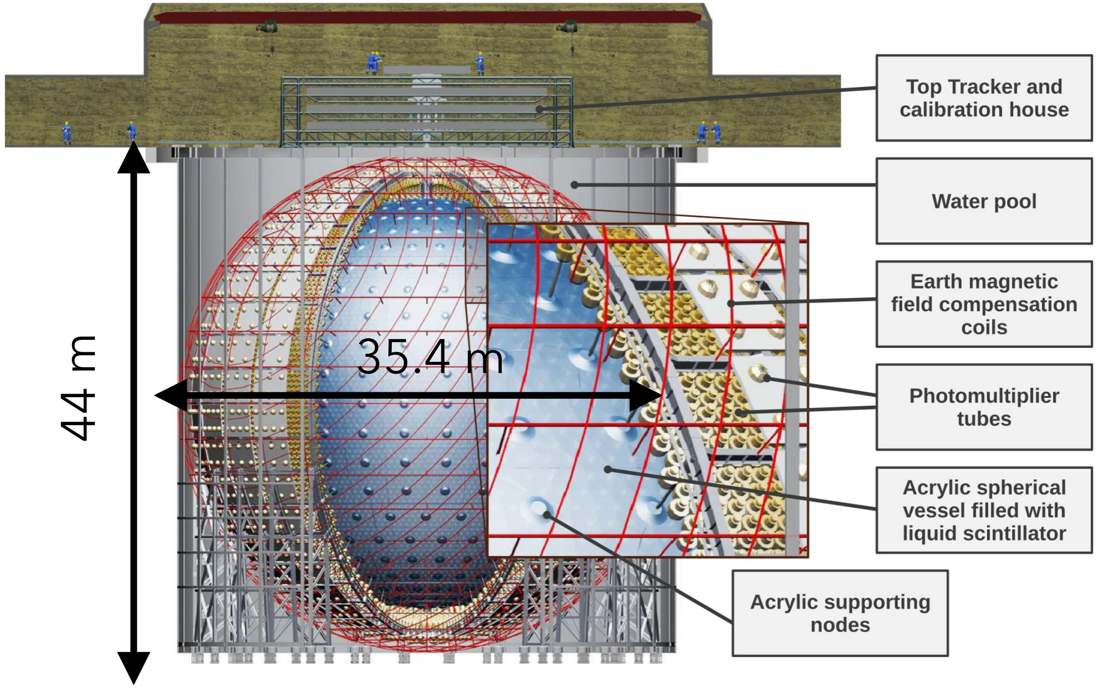
- ✶ 35 kton of high pure water as shield
- ✶ 2400 20″ large-PMTs for active veto

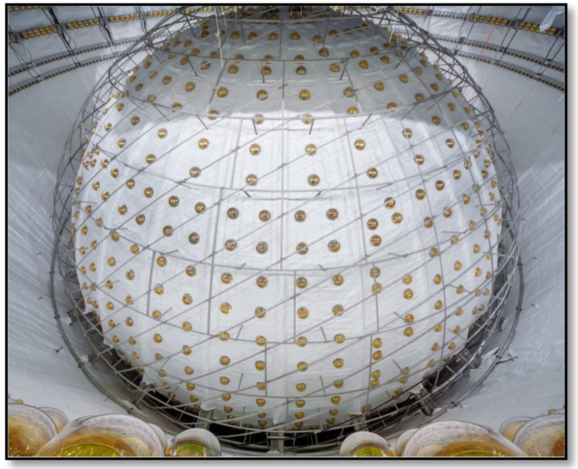
Top Tracker (TT)

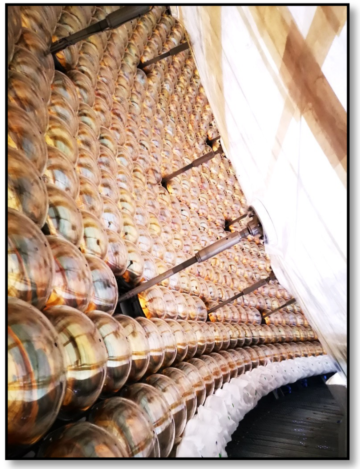
- ✶ 3 plastic scintillator layers (coverage ~30% of muons)

Calibration system

- ✶ More than 6 sources + laser

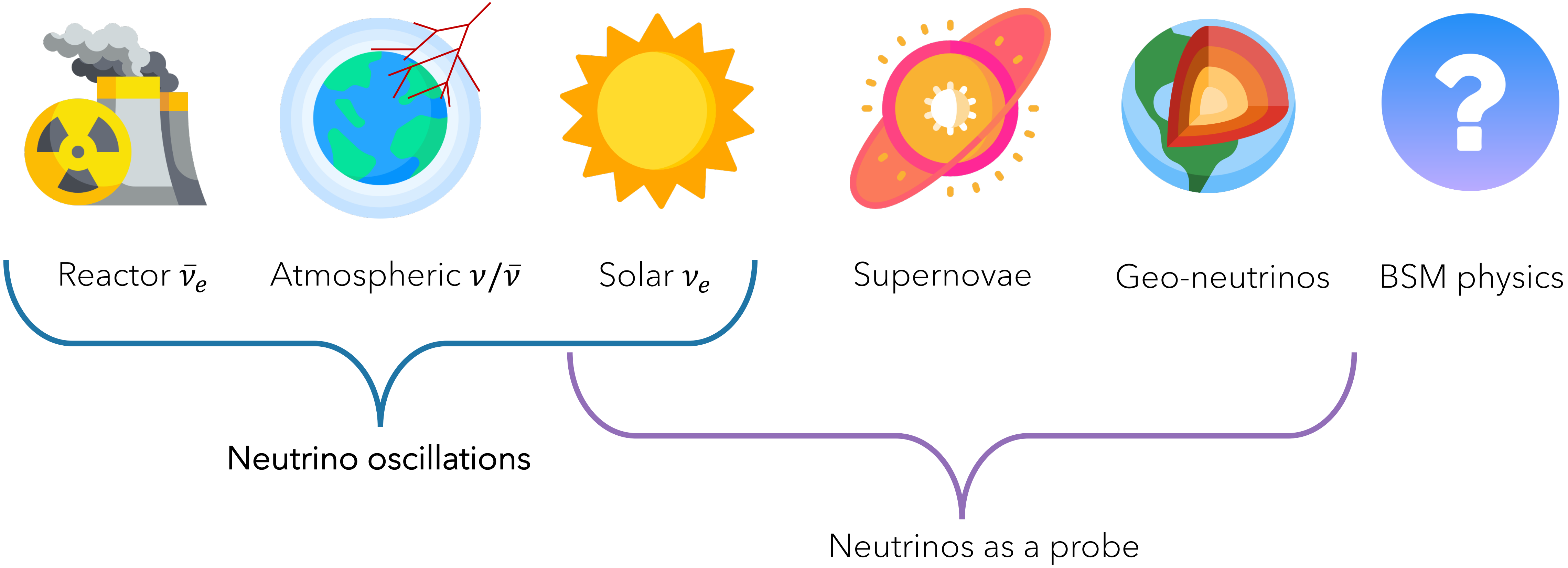






JUNO PHYSICS PROGRAM

JUNO has a **rich physics program** and will detect neutrinos from several sources.



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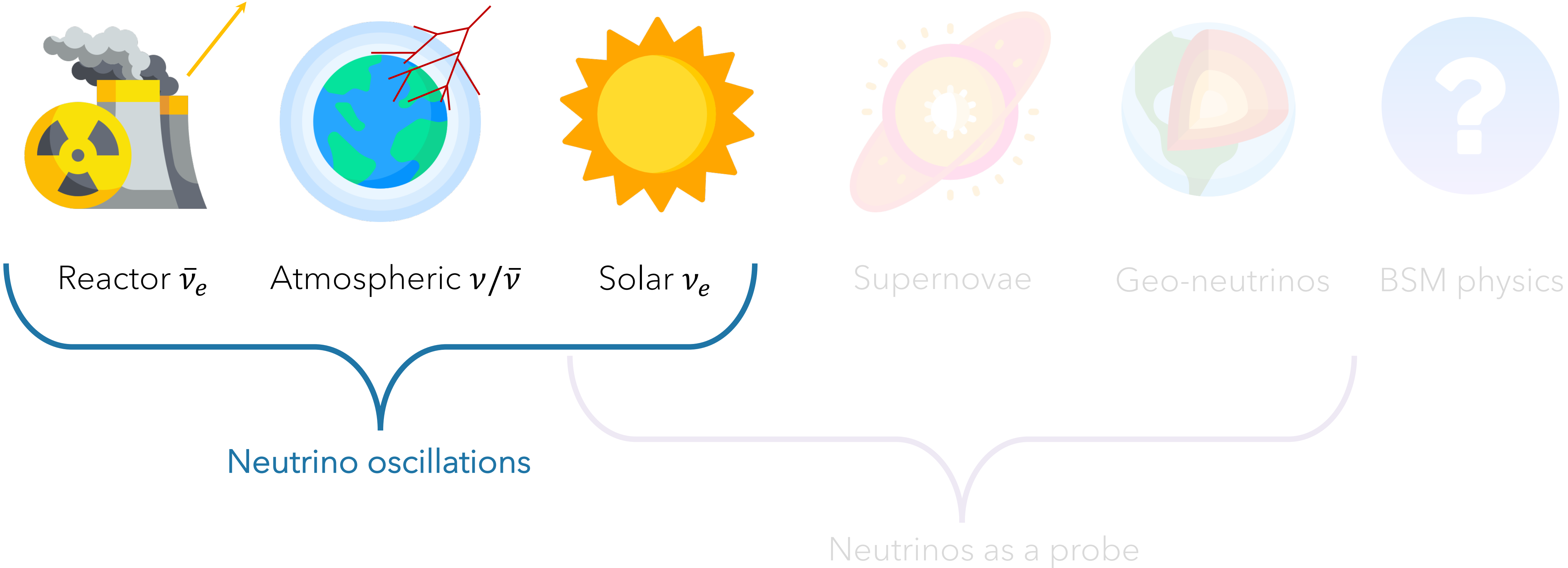
Han Zhang's talk



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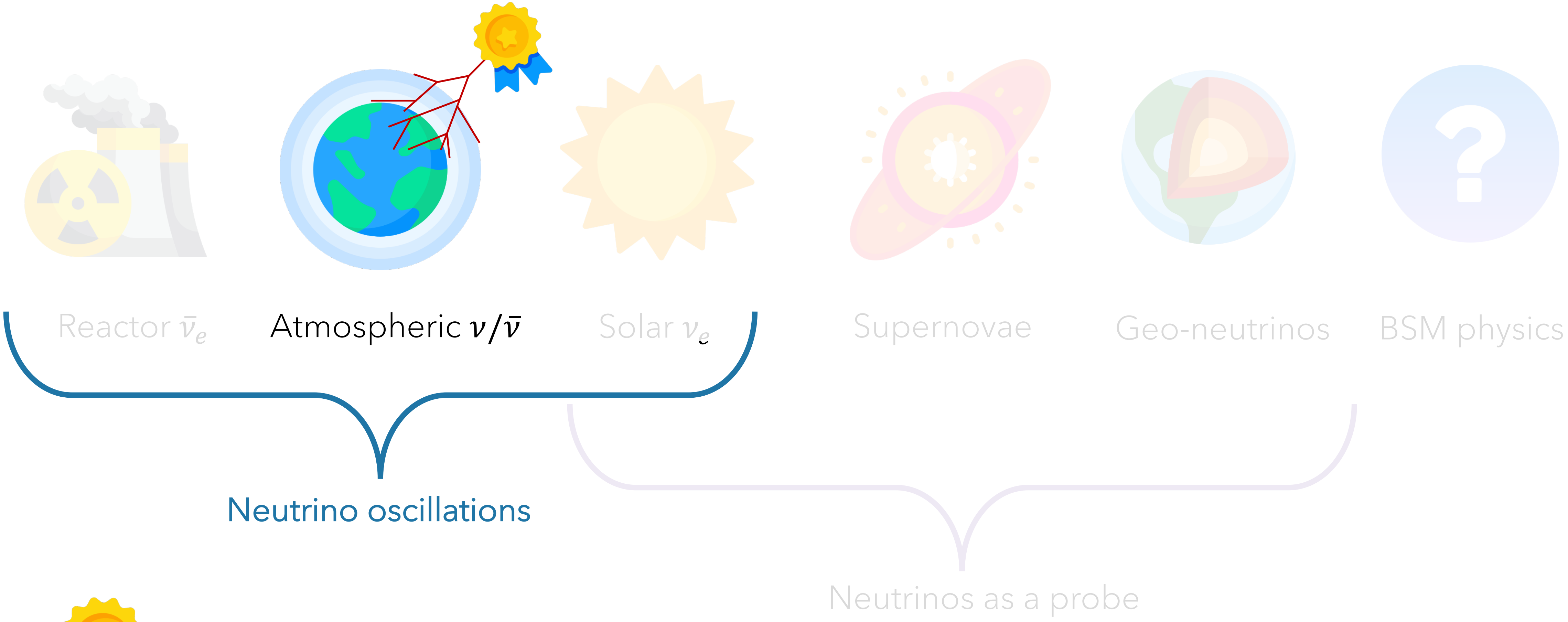
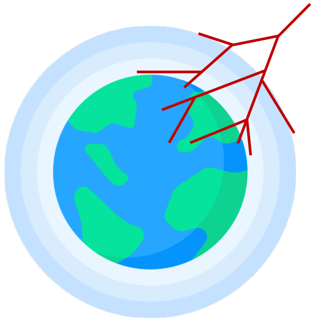


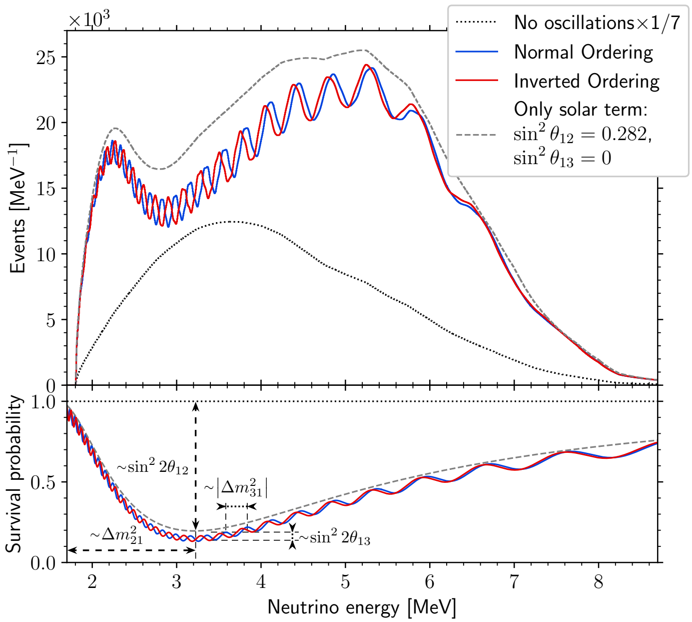
In this presentation focus on atmospheric neutrinos

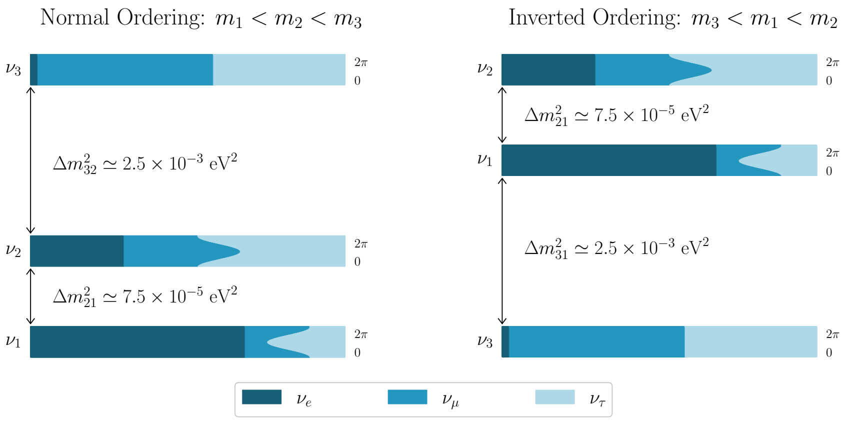
WHY ATMOSPHERIC NEUTRINOS IN JUNO?

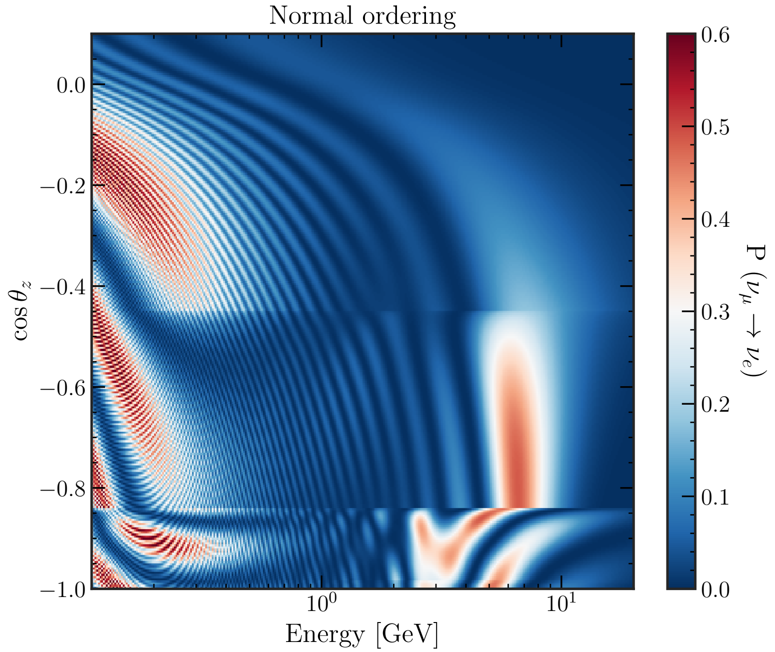
Reactor $\bar{\nu}_e$: NMO sensitivity through **interference**, oscillations by small and large mass splittings

Atmospheric $\nu/\bar{\nu}$: NMO sensitivity through matter effects, **MSW** effect





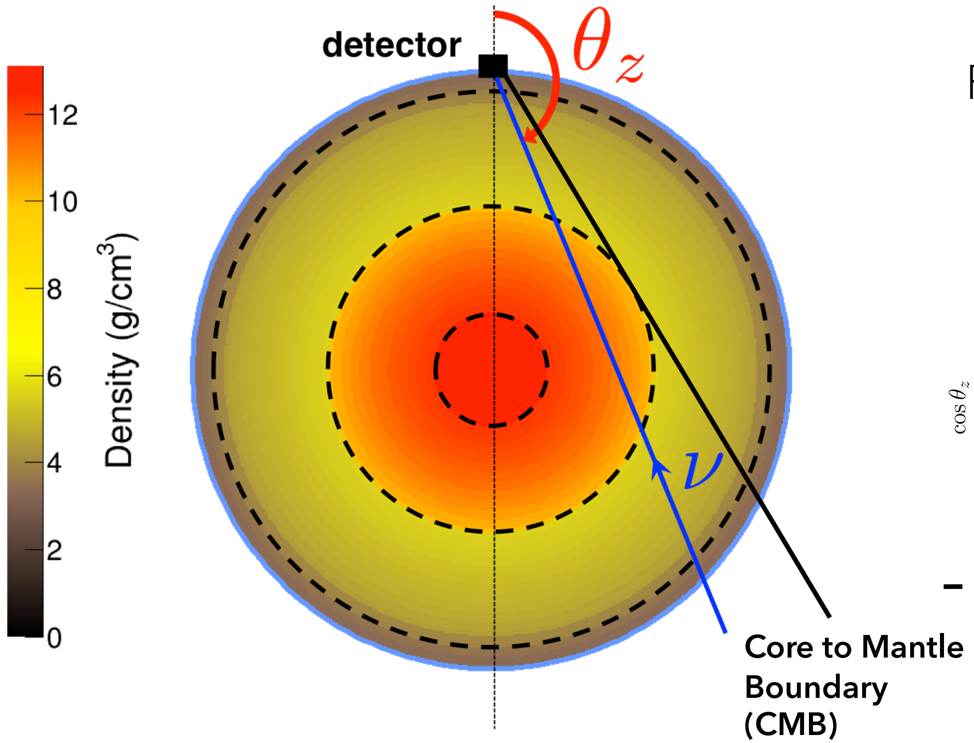




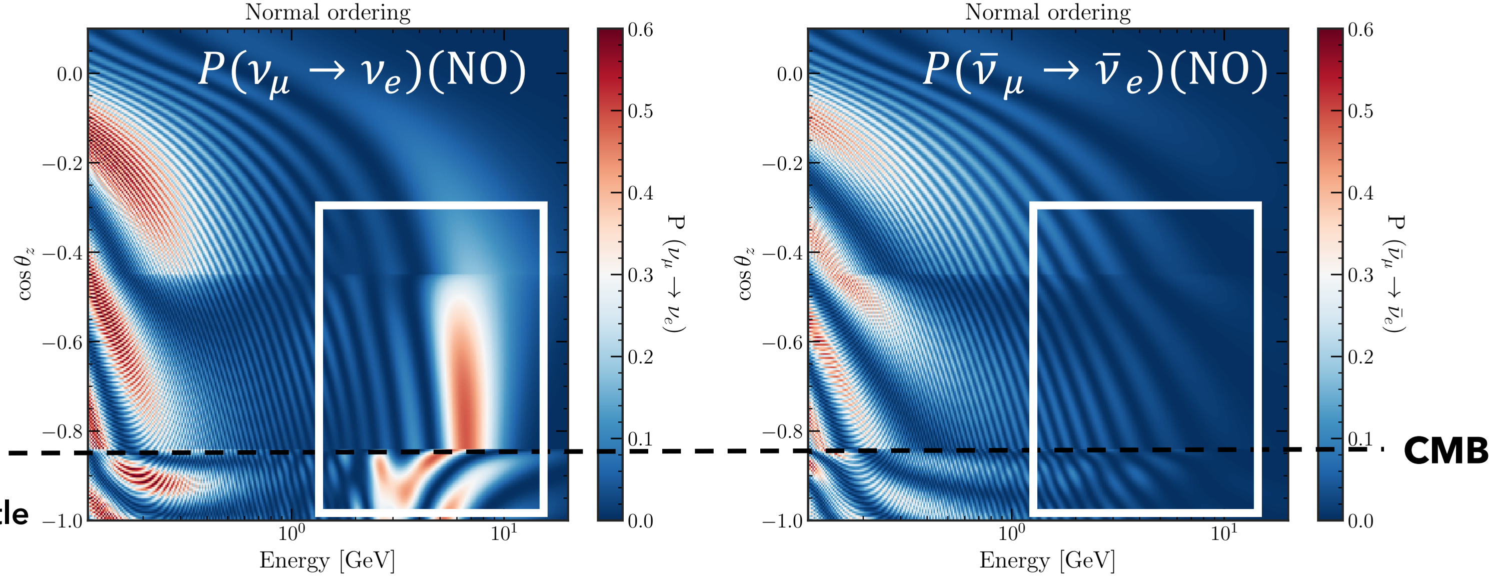
- ✶ **Atmospheric neutrinos** provide **independent sensitivity to NMO** via matter effects
- ✶ Combining reactor antineutrinos and atmospheric neutrinos oscillations can **maximize JUNO NMO sensitivity**

ATMOSPHERIC NEUTRINO OSCILLATIONS

- ✶ Atmospheric neutrinos (of several GeV) going through Earth's matter undergo MSW effects
- ✶ Neutrino **oscillation probability** $P = f\left(\frac{L}{E}\right), L \sim \cos\theta$, depends on the neutrino **energy, incident zenith angle** θ, and **type/flavor** → **Neutrino directionality** and **flavor identification** are critical

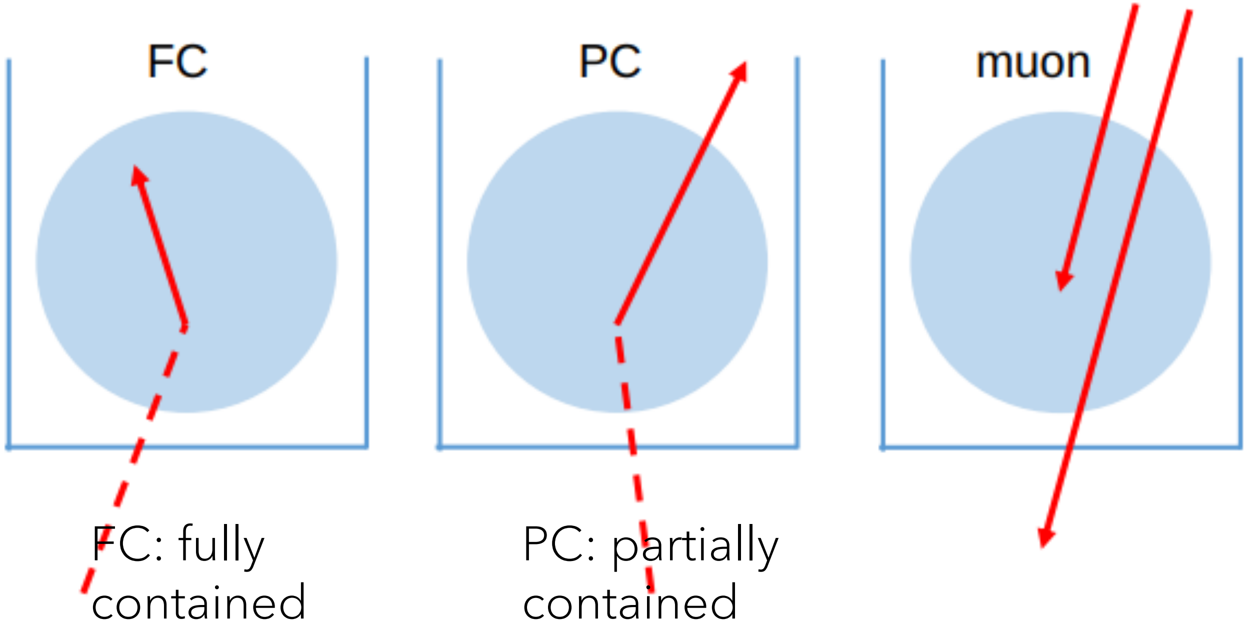


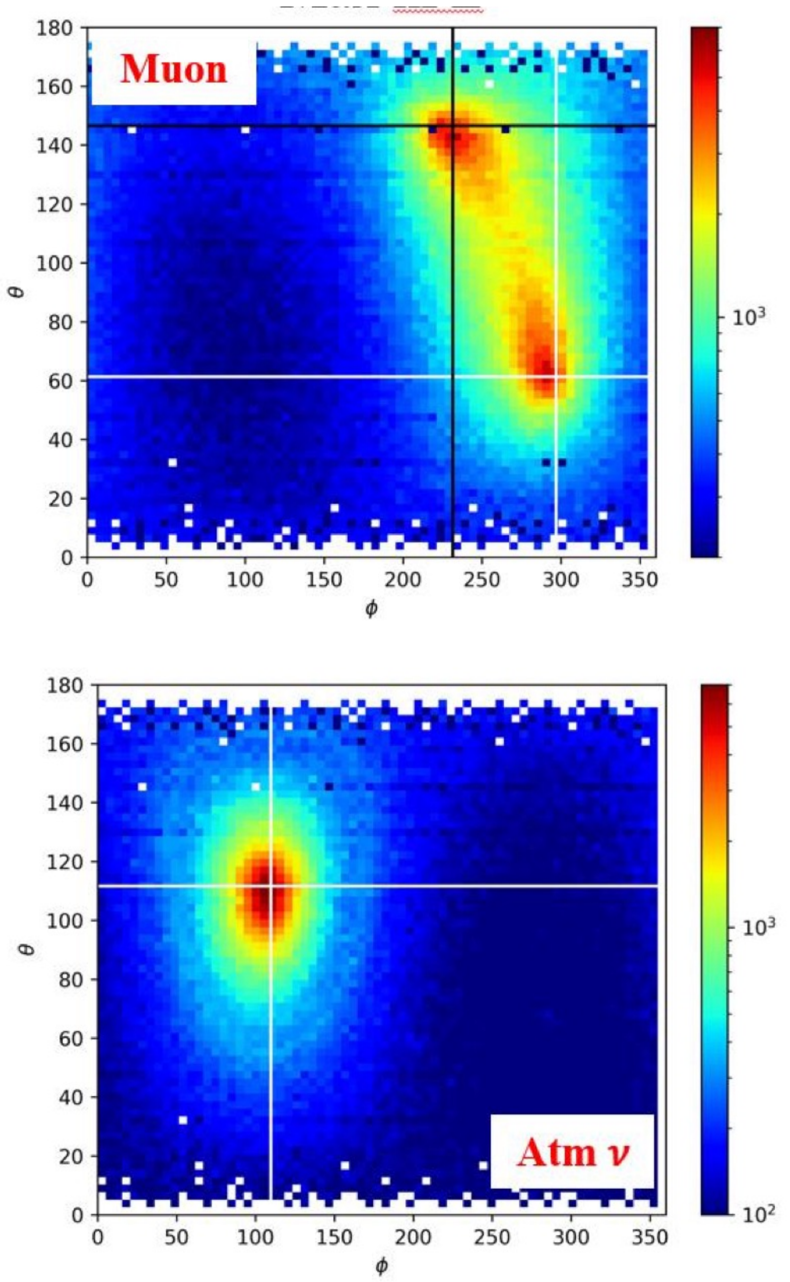
Flavor transition enhanced for **neutrinos** (antineutrinos) if **NO** (IO)



MUONS vs ATMOSPHERIC NEUTRINOS

- ✶ Atmospheric neutrino interactions in JUNO LS: ~ 10/day
- ✶ Expected muon rate in CD ~ 5 Hz, good muon selection thanks to CD+WP+TT correlation
- ✶ Remaining muons can be removed using PMT features (charge and time patterns)





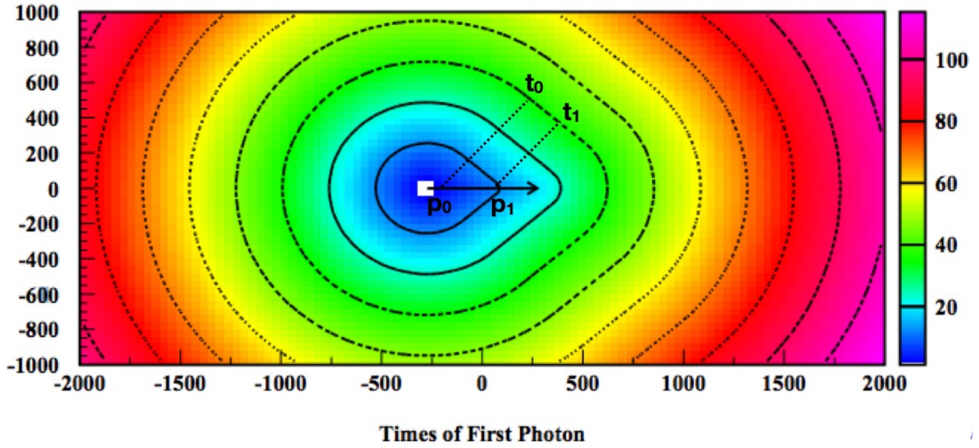
LIQUID SCINTILLATOR FOR ATMOSPHERIC NEUTRINOS

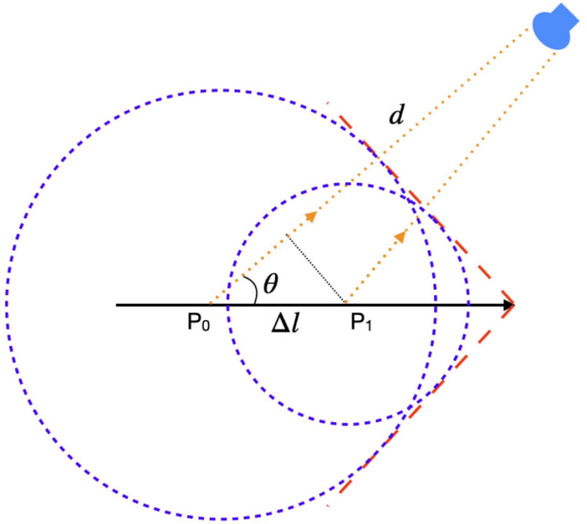
- ✶ First measurement of atmospheric neutrinos with a LS detector → usually designed with low-energy threshold, good energy resolution, **ideal for low-energy neutrinos**

- ✶ **Directionality measurement** in large homogeneous LS detectors is challenging
  - No direct track information
  - Cherenkov light is only a few percent with respect to scintillation → need to use scintillation light for directionality

If particles travel at a speed faster than the speed of light in LS, scintillation light forms a cone-like front structure → use time information encoded in PMT waveforms

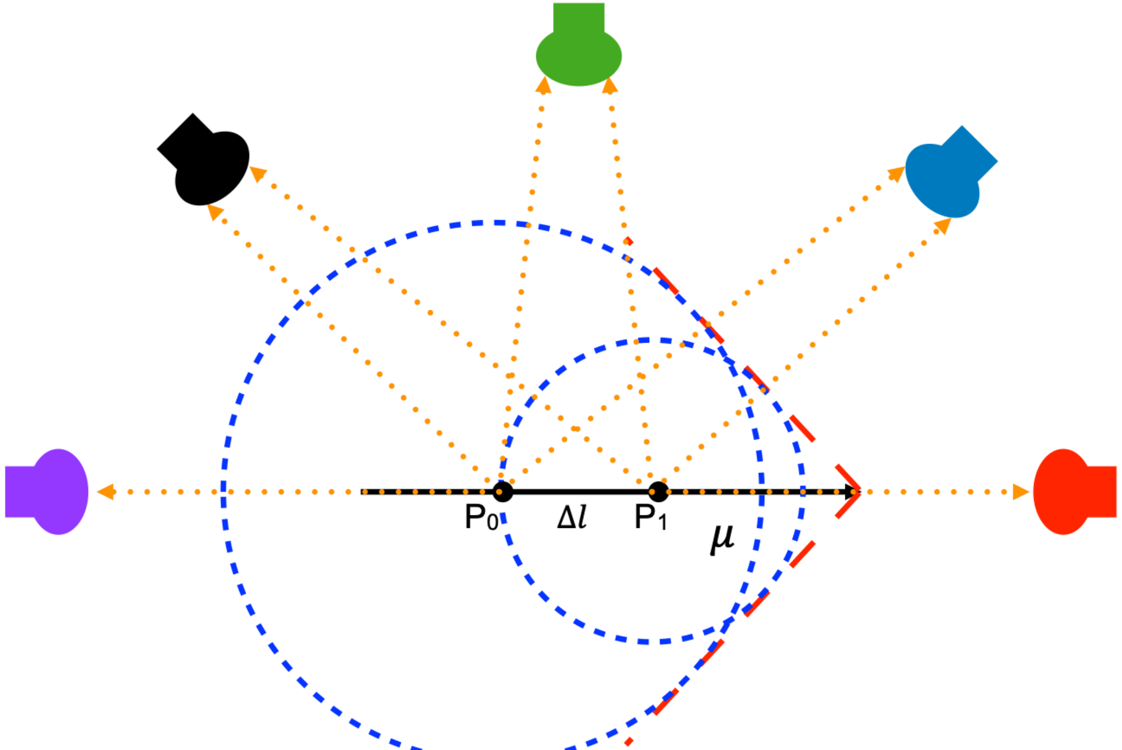
Learned J.G. (arXiv:0902.4009)

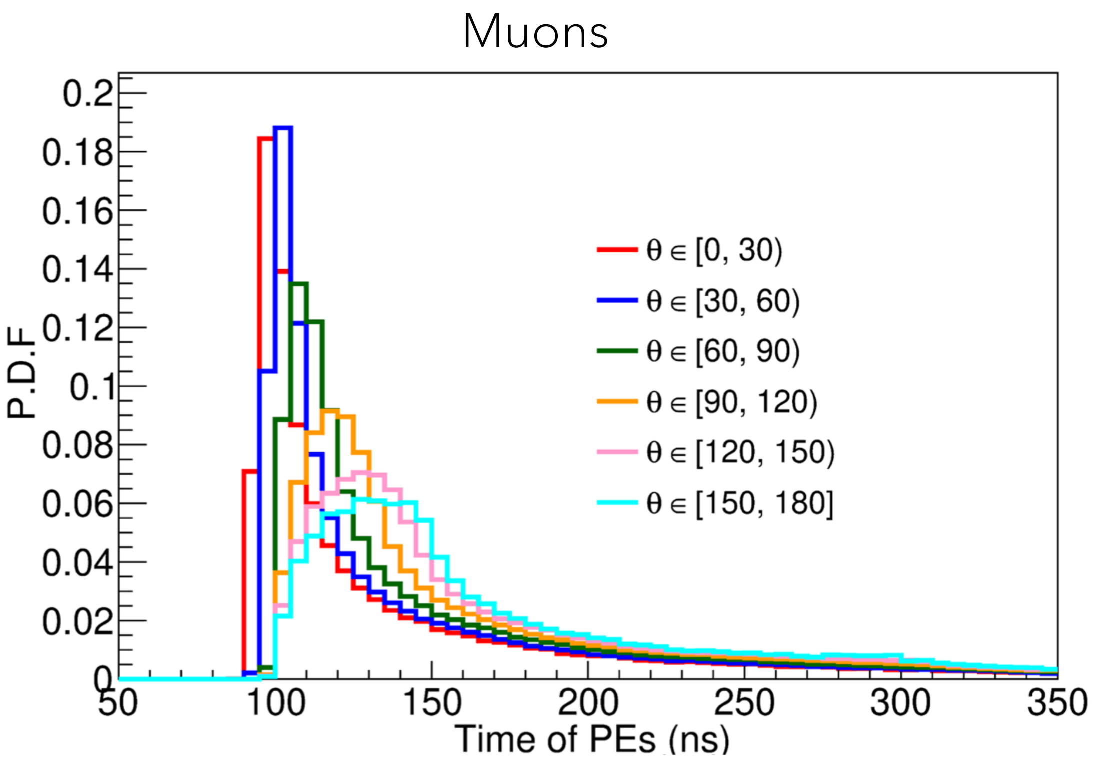




DIRECTION RECONSTRUCTION WITH PMT WAVEFORMS

- Particle directionality information is encoded within the **PMT waveform** → the **first hit time** in PMTs carry event directionality information





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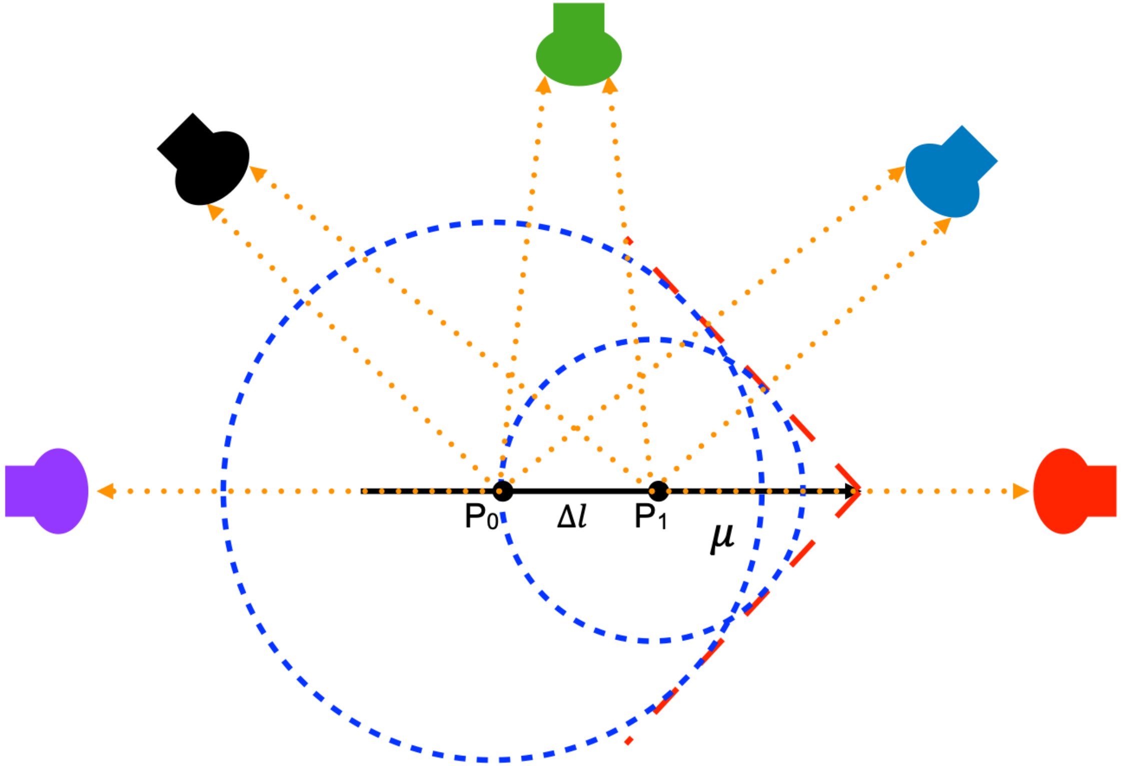
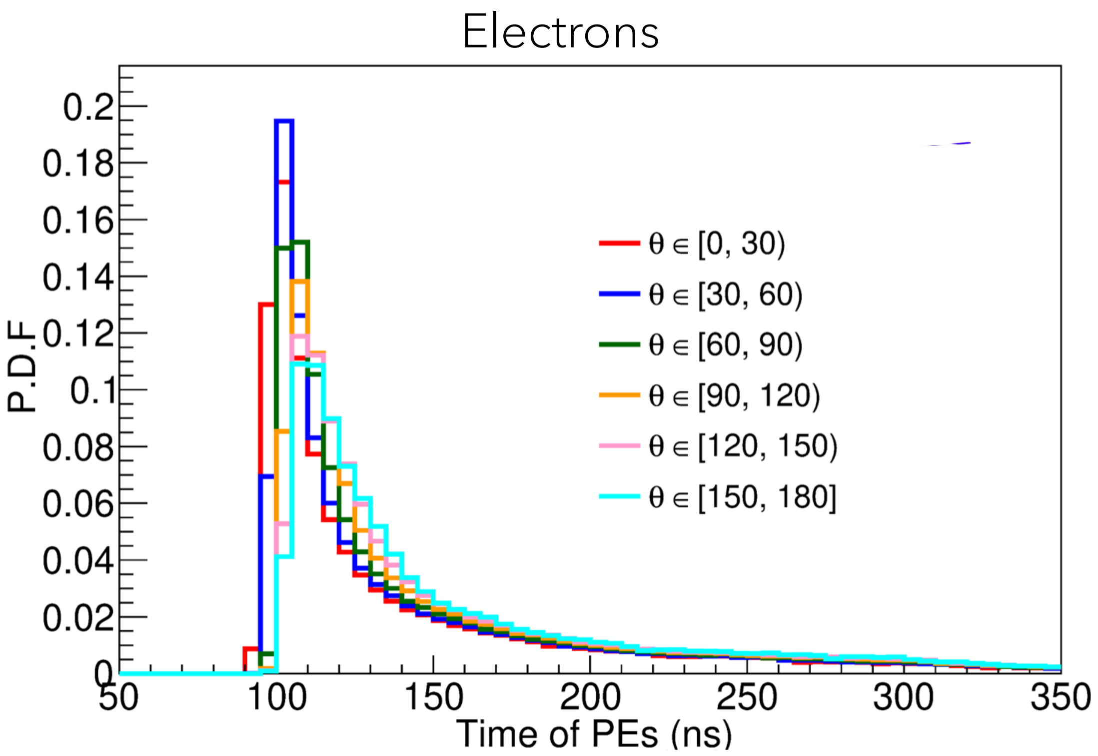


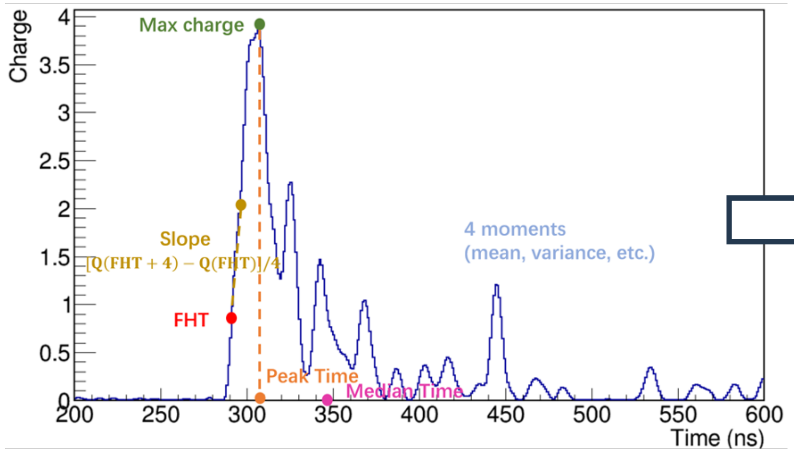


Shape different for electron/muons → useful for PID

MULTIPURPOSE RECONSTRUCTION METHOD

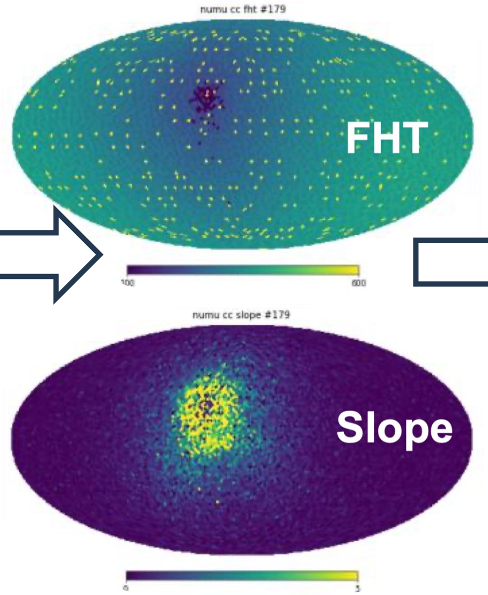
Phys.Rev.D 109 (2024) 5, 052005

✶ Machine learning approach to find neutrino directions from feature patterns through training

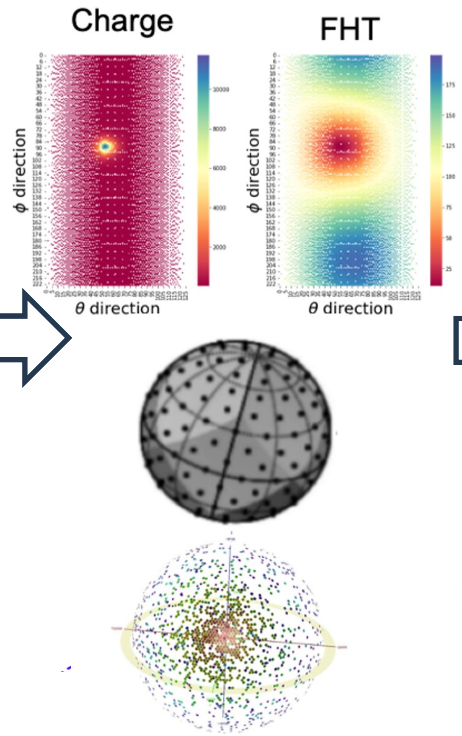


Extract features from waveforms

- First hit time (FHT)
- Total charge
- Average slope in the first 4 ns
- …



Picture of features



Machine learning models

(EfficientNetV2, DeepSphere, PointNet++)

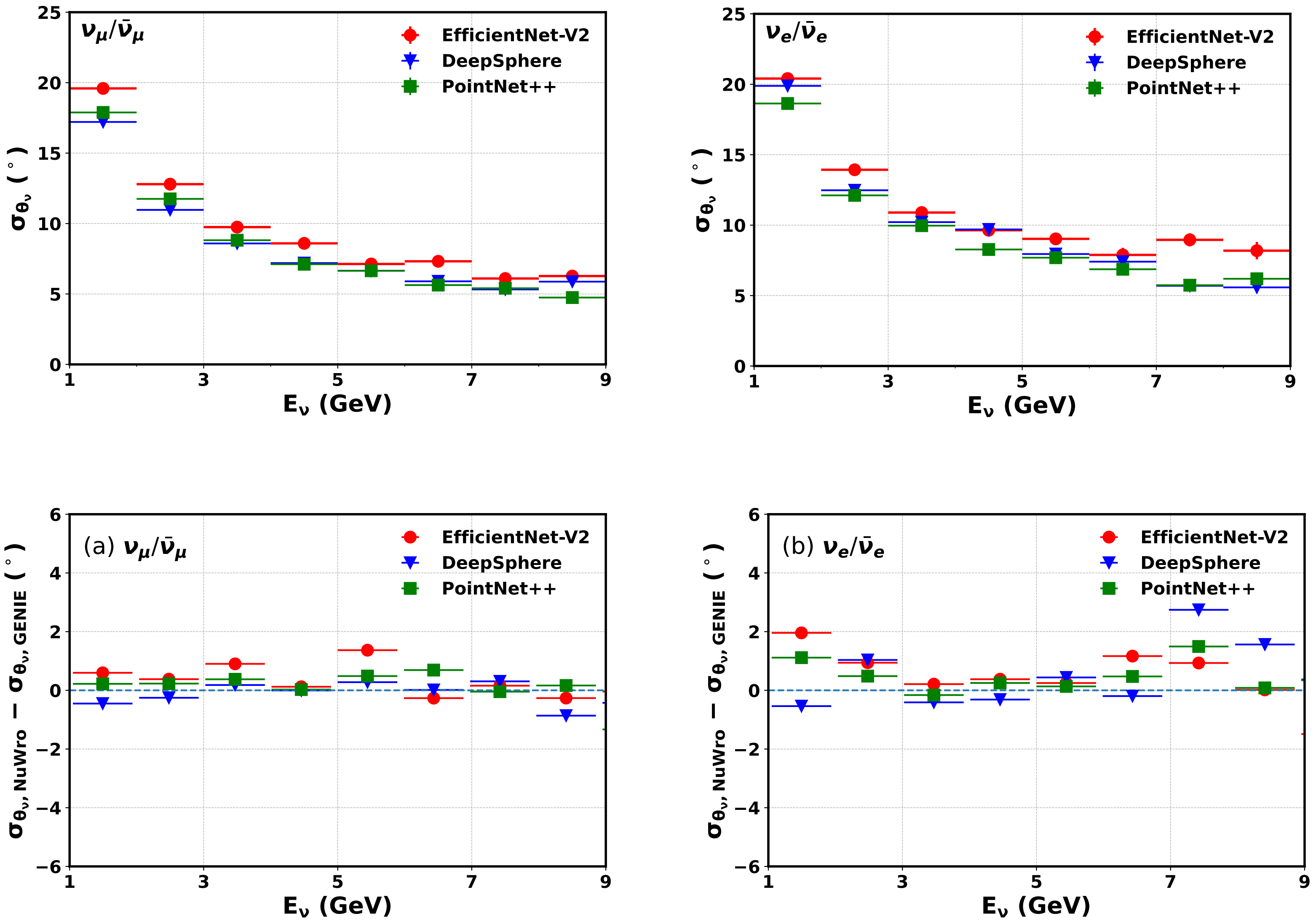
- Direction
- Energy
- Flavor
- Track
- Vertex

ZENITH ANGLE RESOLUTION

Phys.Rev.D 109 (2024) 5, 052005

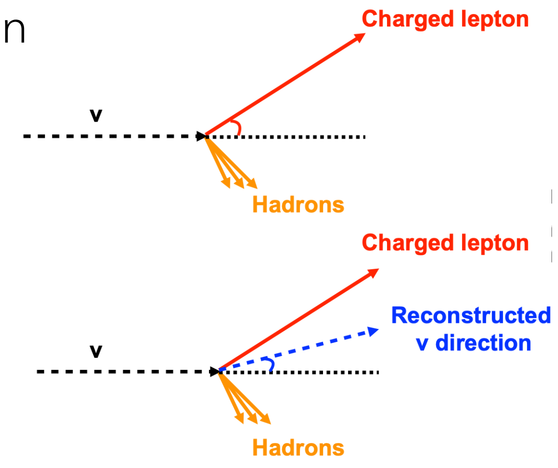
- ✶ For $E_\nu > 3$ GeV, angular resolution is around < 10° for all ML models and for both $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$

- ✶ Interaction model impact: Performance with GENIE and NuWro found to be comparable



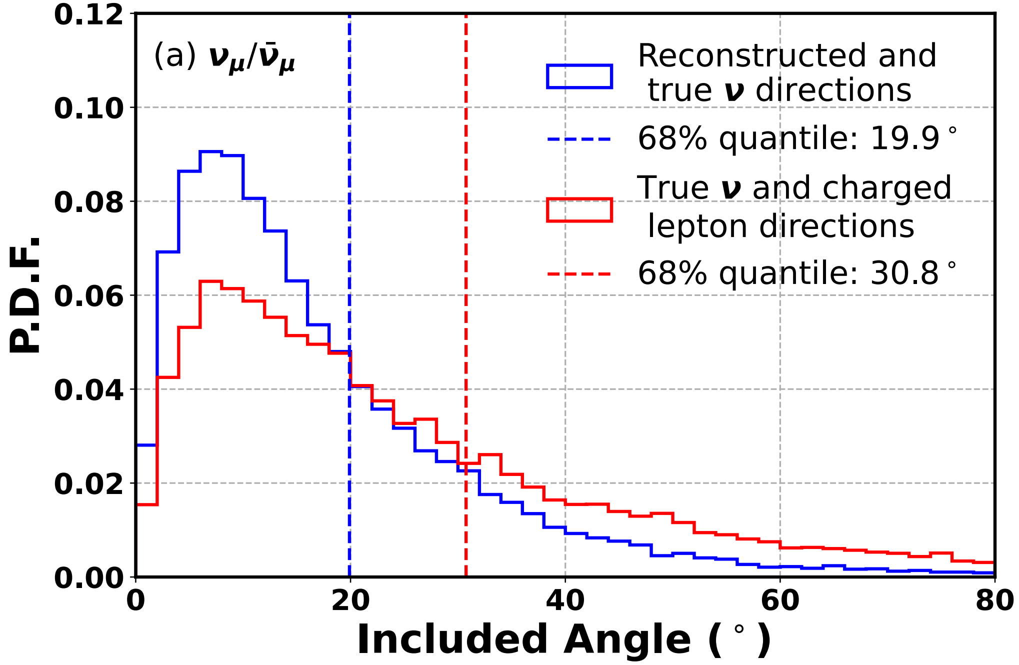
DIRECTION RECONSTRUCTION

- ✶ Both **lepton** and **hadron** information is used in the direction reconstruction



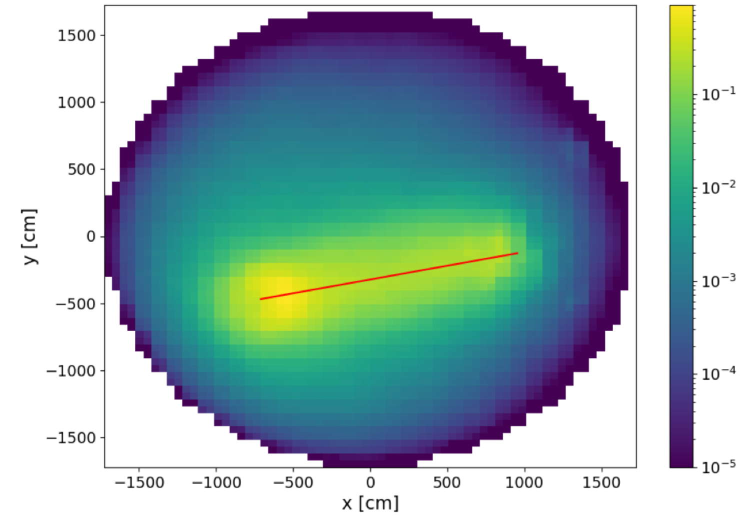
- ✶ **Reconstructed neutrino direction** less smeared from true neutrino direction compared with the charged lepton direction

Phys.Rev.D 109 (2024) 5, 052005



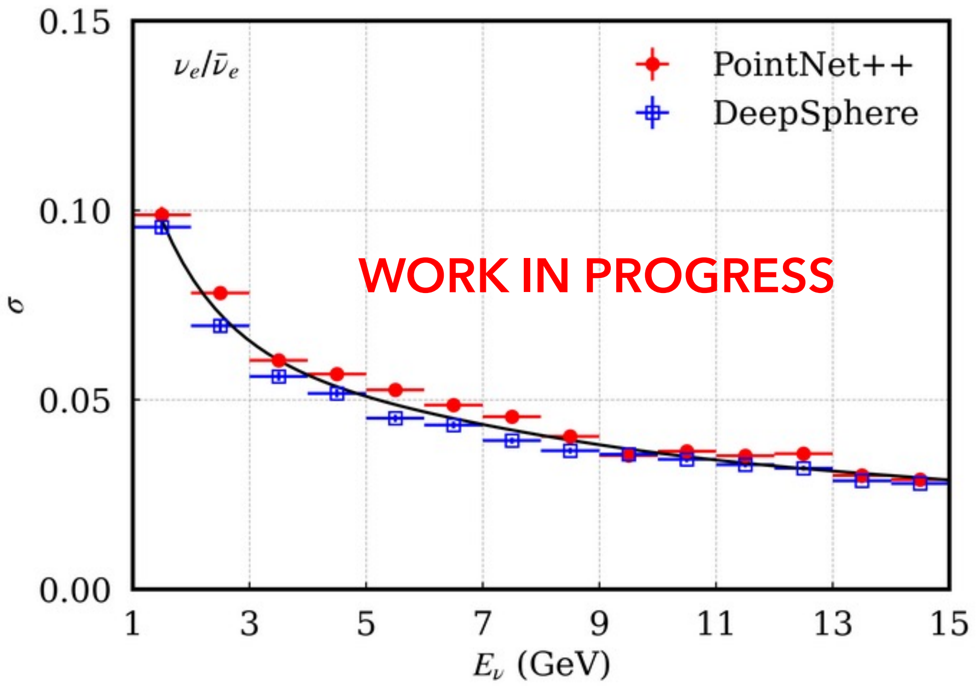
- ✶ Compared with non-ML traditional methods:
  - Likelihood method based on light propagation model to get particle trajectory
  - Similar results, but ML works better for electron neutrinos

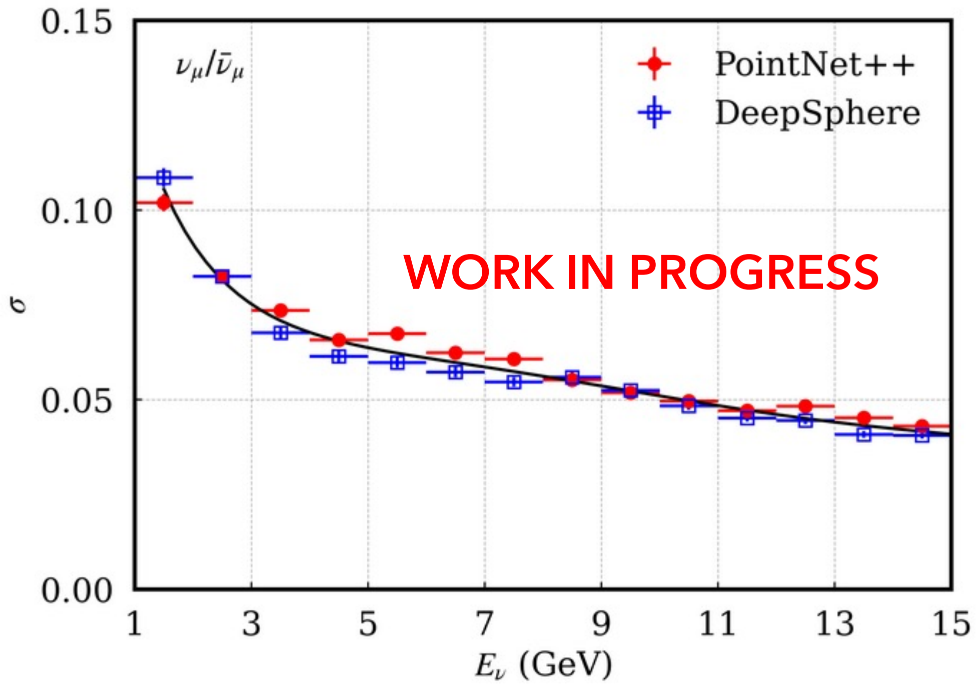
PoS(ICRC2023)1189



ENERGY RECONSTRUCTION

- ✶ Preliminary results: for $E_\nu > 3$ GeV:
  - Better than **6% resolution for electron neutrinos**
  - Better than **8% resolution for muon neutrinos**
- ✶ Investigating two possible strategies for energy reconstruction: reconstruct the visible energy or the neutrino energy for FC CC events → detailed study is on-going for the impact on oscillation analysis

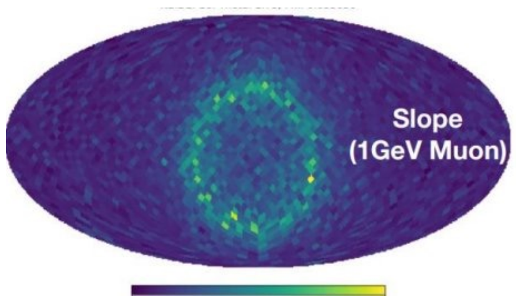


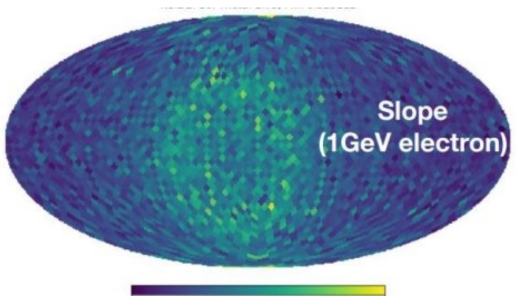


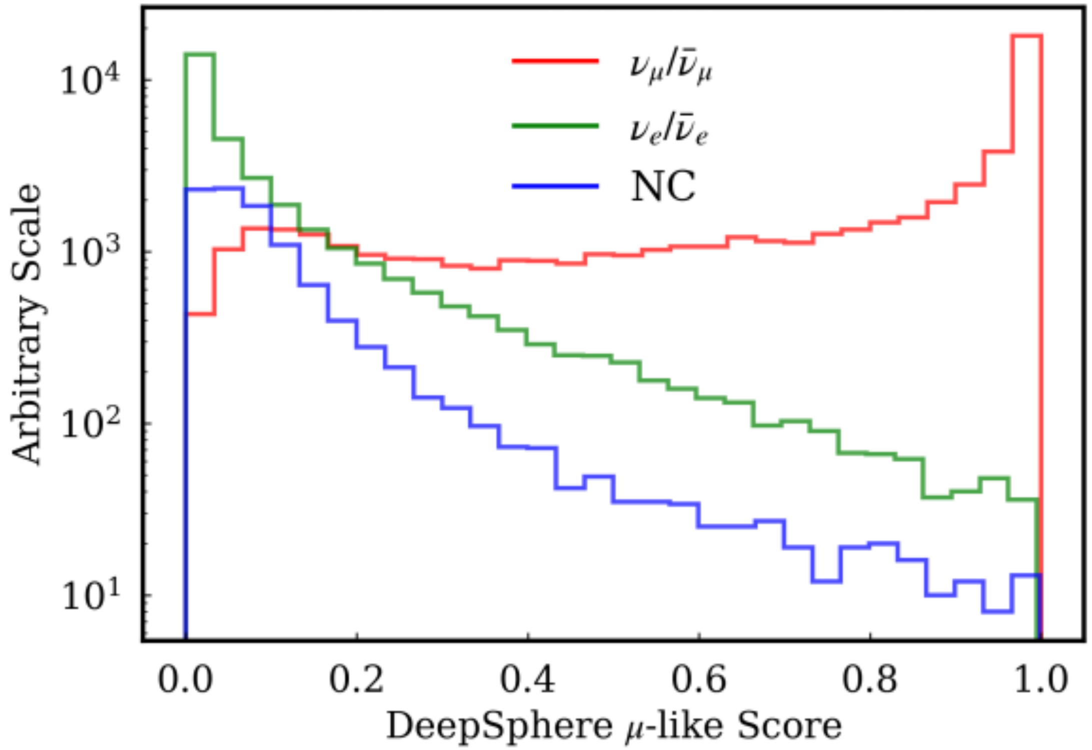
NEUTRINO FLAVOR IDENTIFICATION

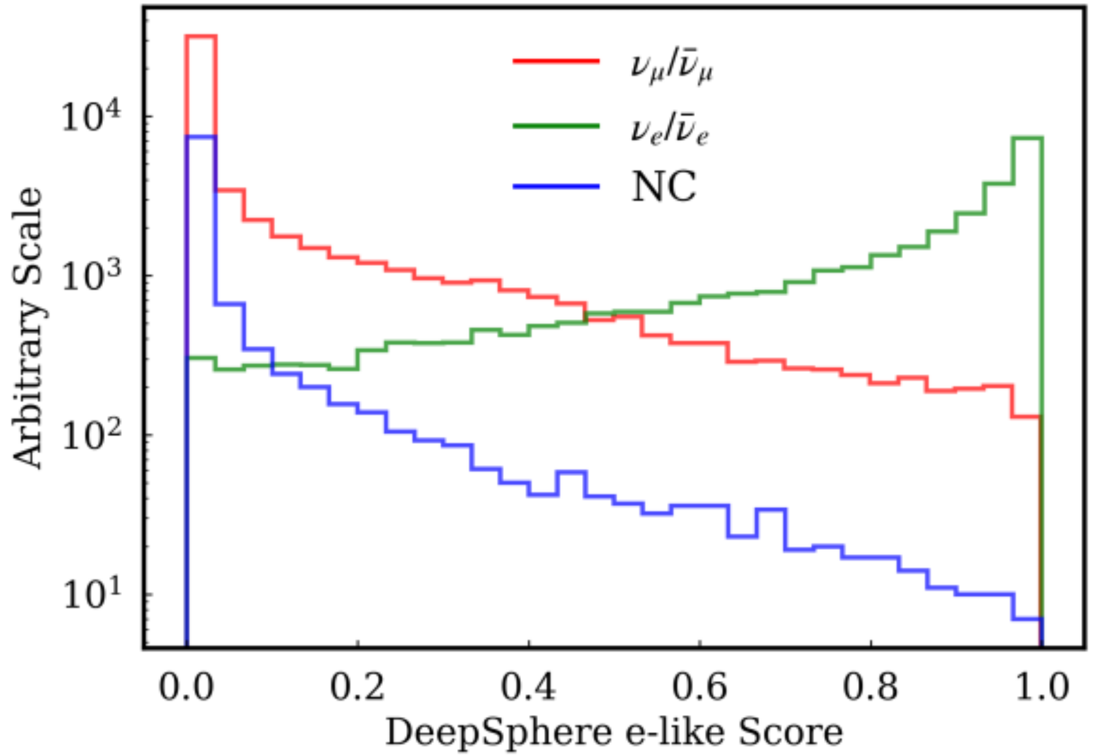
Phys. Rev. D 112, 012018 (2025)

- ✶ Event topology information reflected in the PMT waveforms
- ✶ PMT waveforms are used to classify: $\boldsymbol{\mu}$-like, e-like and NC-like





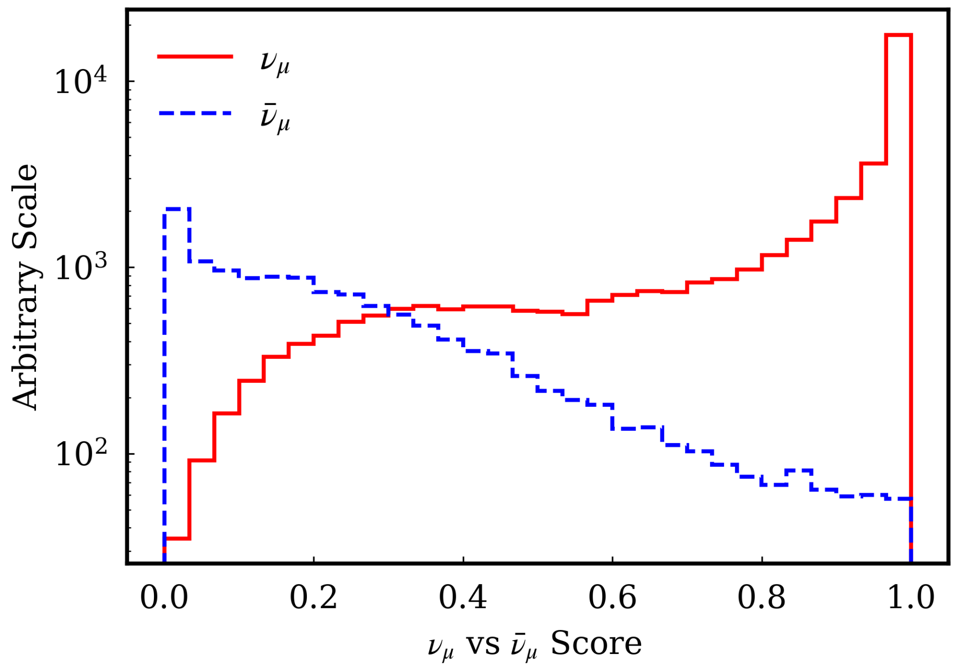


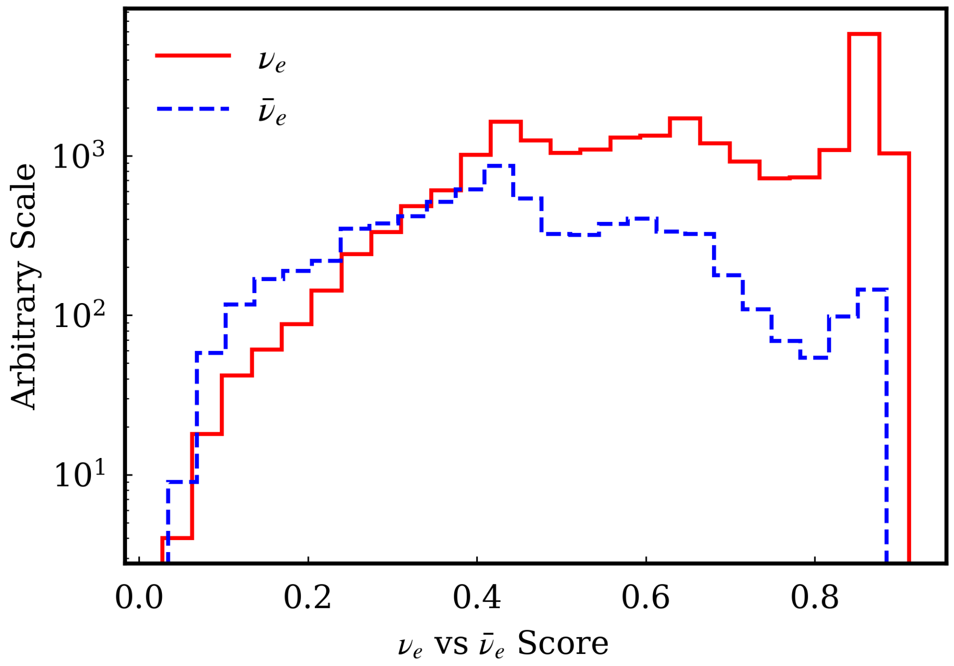


NEUTRINO vs ANTINEUTRINO

Phys. Rev. D 112, 012018 (2025)

- ✶ Antineutrinos transfer less energy to hadrons (less hadronic interaction): encoded in PMT waveform
- ✶ Antineutrino interactions tend to produce more primary neutrons than neutrino interactions → statistically separate ν and $\bar{\nu}$ adding **neutron-capture information**
  - Energy between 2-2.7 MeV
  - Time from prompt trigger between 10 μs and 1 ms



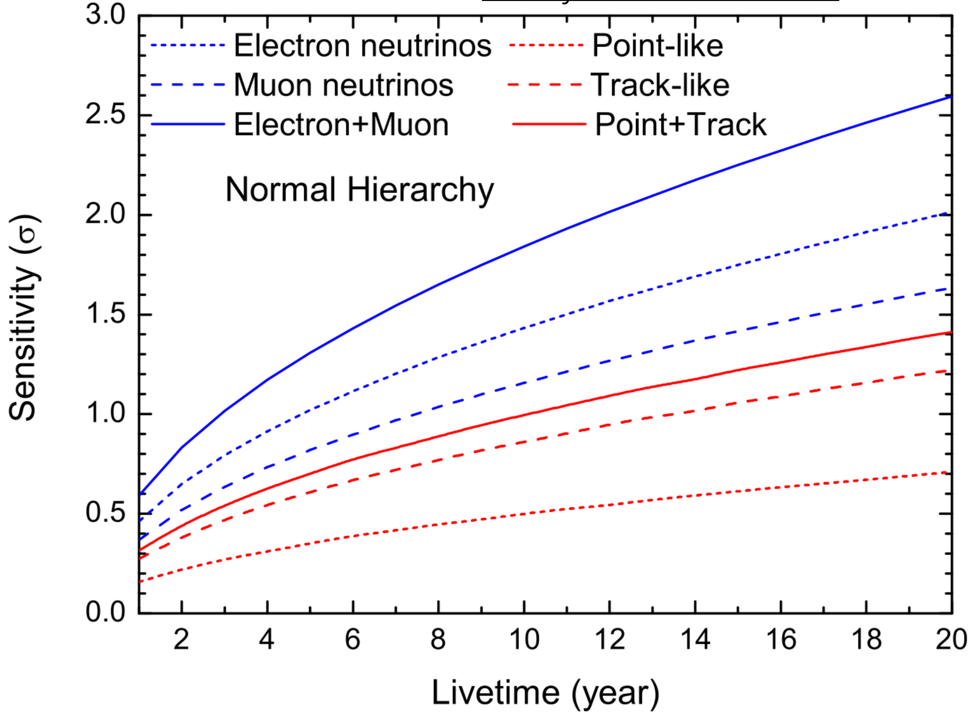


TOWARDS AN UPDATED SENSITIVITY

	Yellow Book "Optimistic case"	Recent Improvements
Directionality	$\sigma_{\theta\mu}=1^\circ$ $\sigma_{\theta\nu}=10^\circ$	$\sigma_{\theta\nu}<10^\circ$ (E_ν>3GeV)
Energy	Visible energy	Neurino energy for FC events
e-like Event Selection	E_{vis} > 1GeV, $Y_{vis}=E_h/E_{vis}$ < 0.5	ML-based selection allowing for more stats
Classification	Simple classification with Michel e, Y_{vis} cuts	ν vs $\bar{\nu}$: 60%~80% eff.
Sensitivity	1.8 σ in 10 years	**To be updated**

From Q. Yan talk at NuFact 2025

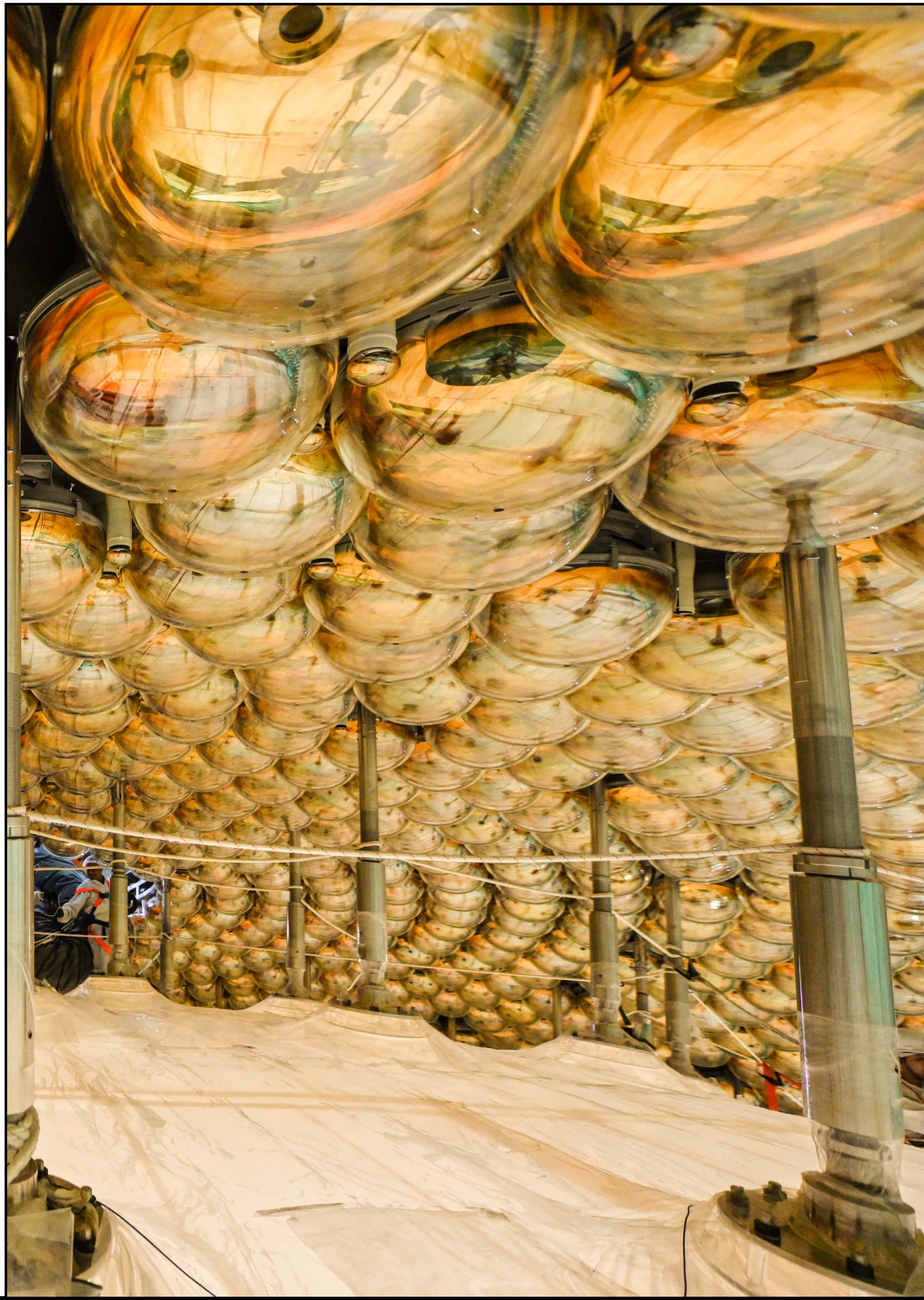
J. Phys. G. 43 030401



- ✶ Recent updates in reconstruction and event identification
- ✶ Re-evaluation of sensitivity in progress

CONCLUSIONS

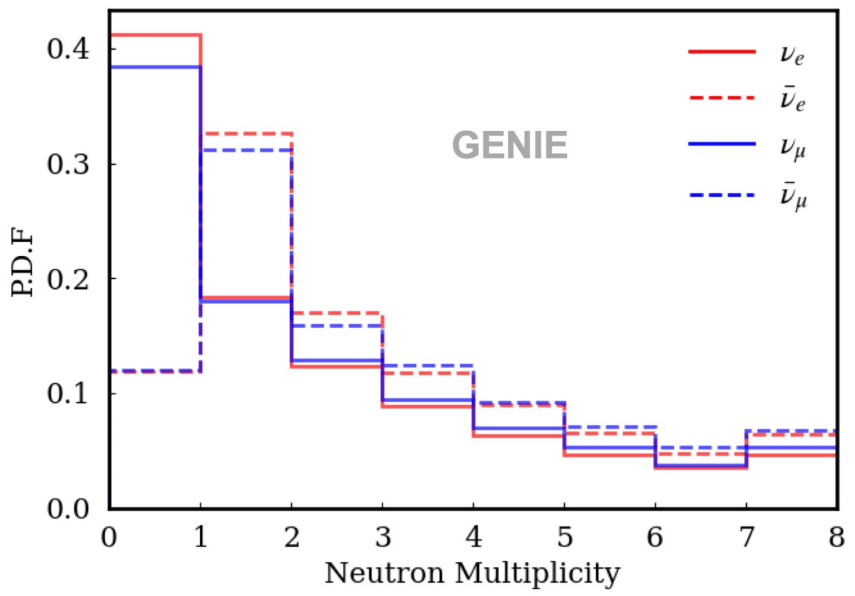
- ✶ **First measurement** of **atmospheric neutrinos** with a LS detector → sub-GeV to multi-GeV energy range
- ✶ **NMO through matter effects**, complementary to reactor antineutrinos, boost the overall NMO sensitivity
- ✶ **New atmospheric neutrinos study in JUNO ongoing** with the latest and more realistic detector response → paper coming soon
  - Progress in event reconstruction and identification
  - Crosschecked with ML and non-ML methods
  - Systematic uncertainties under study
- ✶ **Construction of the JUNO detector is fully completed →** stay tuned for exciting physics results!

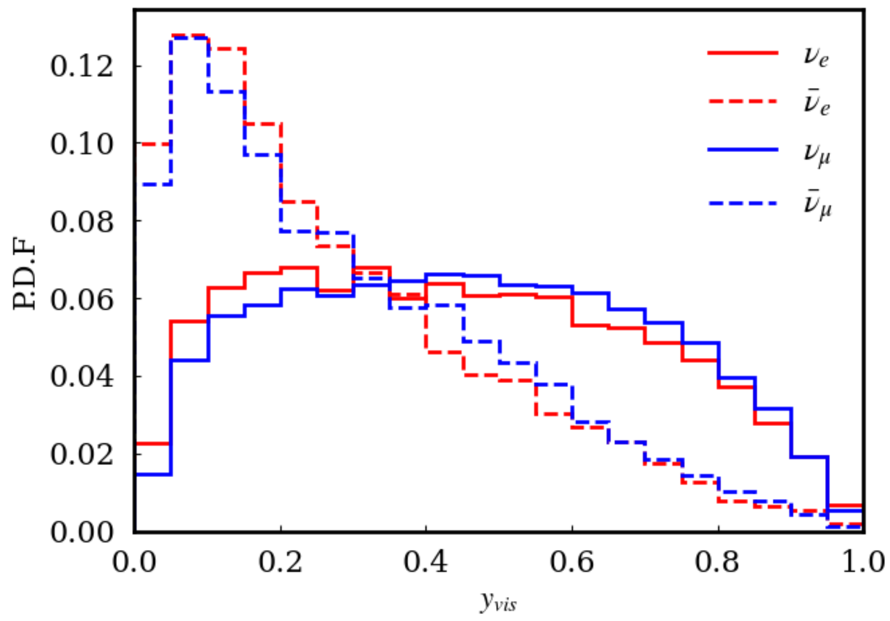


BACKUP

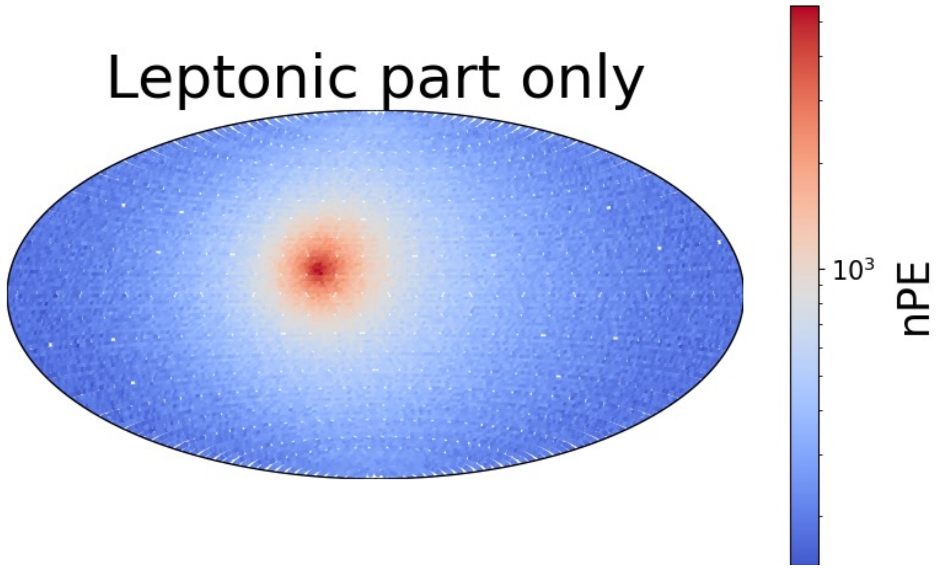
NEUTRINO vs ANTINEUTRINO

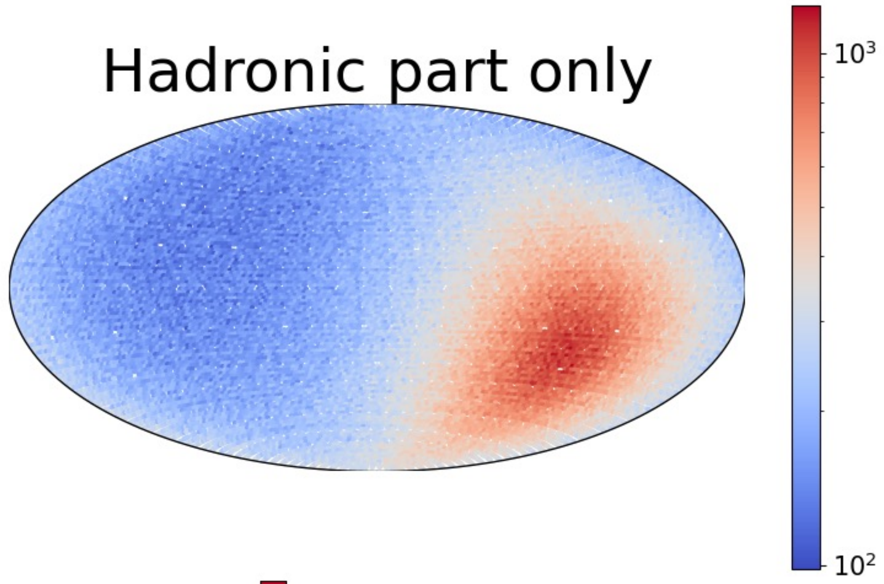
	ν_μ-CC	$\bar{\nu}_\mu$-CC
QE	$\nu_\mu + n \to \mu^- + p$	$\bar{\nu}_\mu + p \to \mu^+ + n$
RES	$\nu_\mu + p \to \mu^- + p + \pi^+$	$\bar{\nu}_\mu + p \to \mu^+ + p + \pi^-$
	$\nu_\mu + n \to \mu^- + p + \pi^0$	$\bar{\nu}_\mu + p \to \mu^+ + n + \pi^0$
	$\nu_\mu + n \to \mu^- + n + \pi^+$	$\bar{\nu}_\mu + n \to \mu^+ + n + \pi^-$
DIS	$\nu_\mu + N \to \mu^- + X$	$\bar{\nu}_\mu + N \to \mu^+ + X$

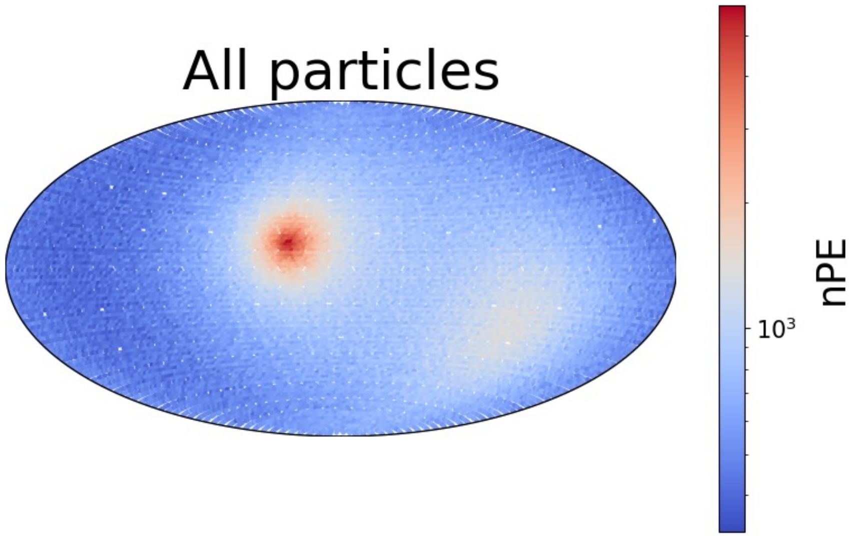




NEUTRINO vs ANTINEUTRINO





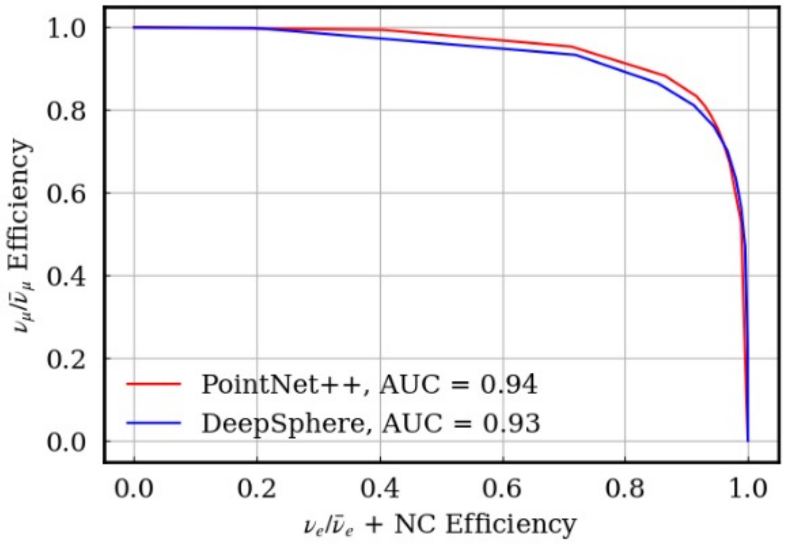


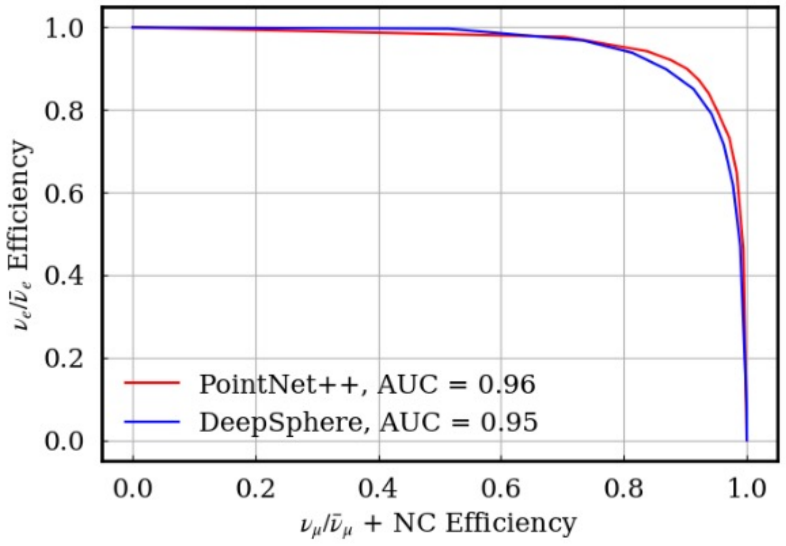
MAJOR IMPROVEMENTS IN DETECTOR RESPONSE

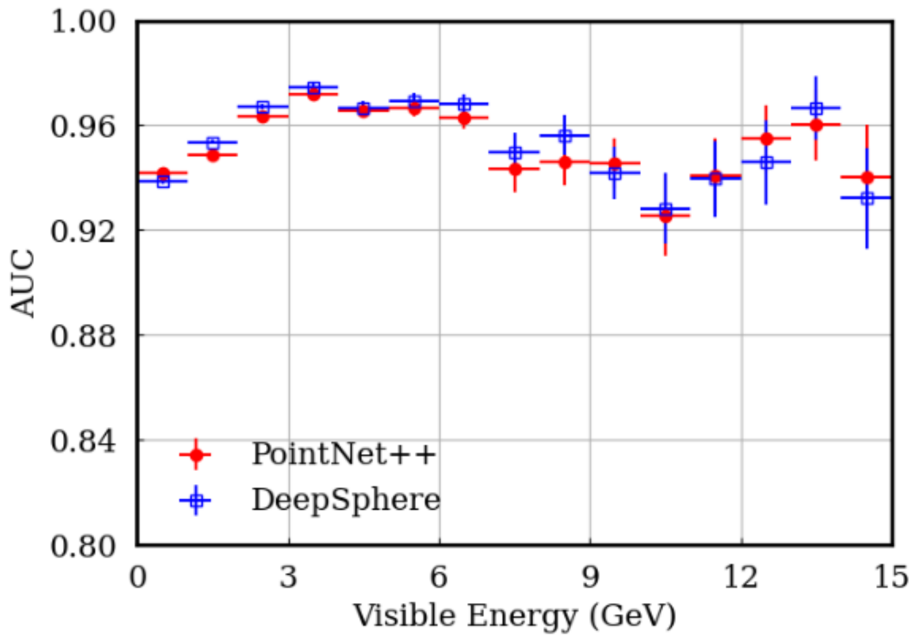
Detector response	Previous estimate	New developments	New features used
Event selection	ν_e: Evis > 1 GeV $Y_{vis} = E_{had}/E_{vis} < 0$ ν_μ: $L\mu$ > 5 m	**E_{vis} > 1 GeV** ~30% more statistics	
Reconstruction (energy and direction)	**$\sigma_{Evis} = 1\%/\sqrt{E_{vis}}$** **$\nu_e : \sigma_{\theta\nu e} = 10^\circ$** **$\nu_\mu : \sigma_{\theta\mu} = 1^\circ$**	E_ν reconstruction instead of E_{vis} **$\sigma_{\theta\nu} < 10^\circ$ (E_ν > 4 GeV)** E_ν dependent	ML-based on PMT features: first hit time, time and charge at peak in waveform
Particle identification	**NC/CCν_e/CCν_μ → 100%** neutrino / anti-neutrino: → based on michel electron N_e and Y_{vis}	**80–95% efficiency** E_ν dependent **60% ~80% efficiency:** better separation neutrino / anti-neutrino	ML-based on PMT features for primary triggers and neutron (secondary) triggers

PERFOMANCE OF FLAVOR IDENTIFICATION

The steeper the Receiver operating characteristic (ROC), better the separation

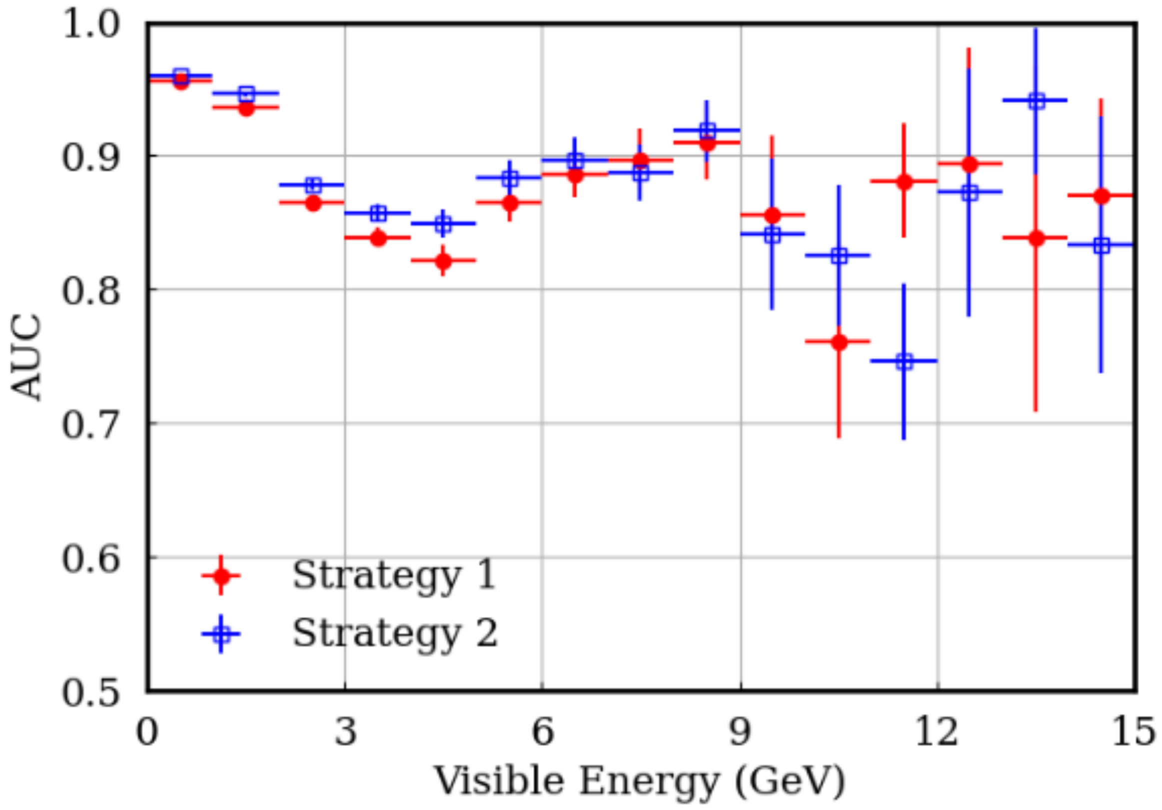




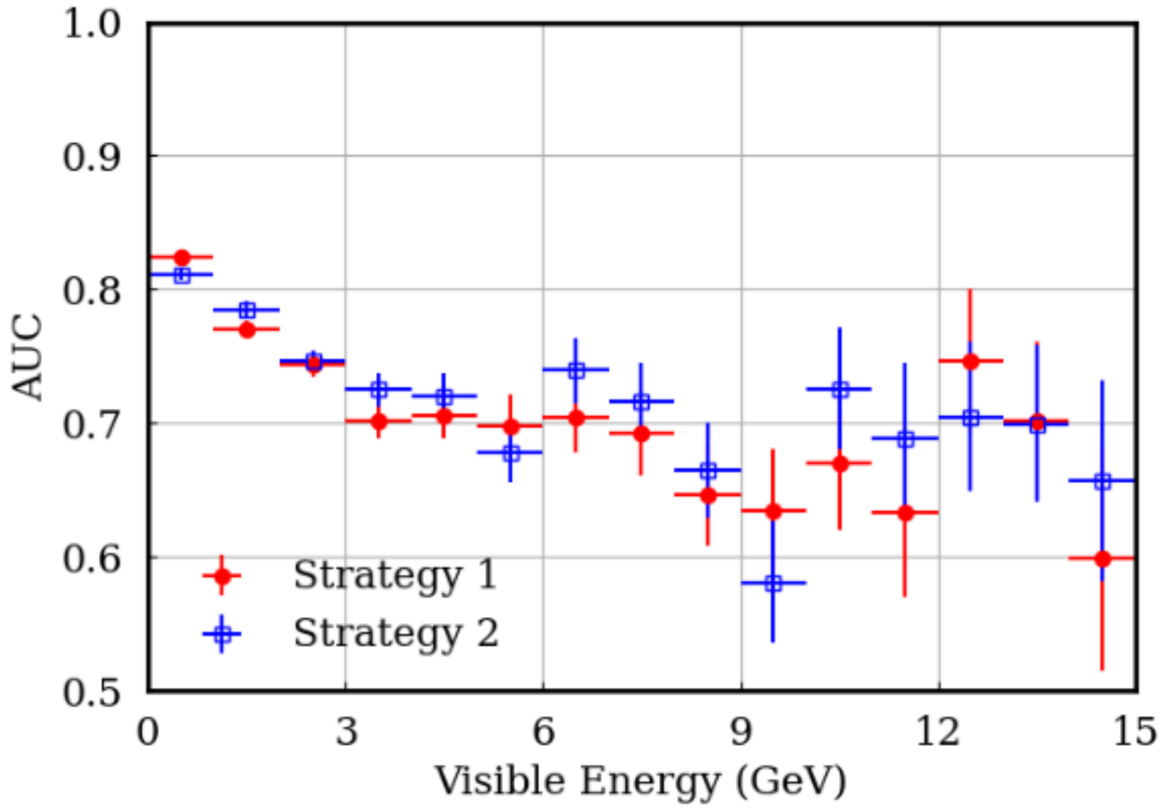


- The performance of two different ML models are similar
- For the oscillation analysis the score can be tuned depending on the requirement

PERFOMANCE OF PID



(a) $\nu_\mu/\bar{\nu}_\mu$ identification

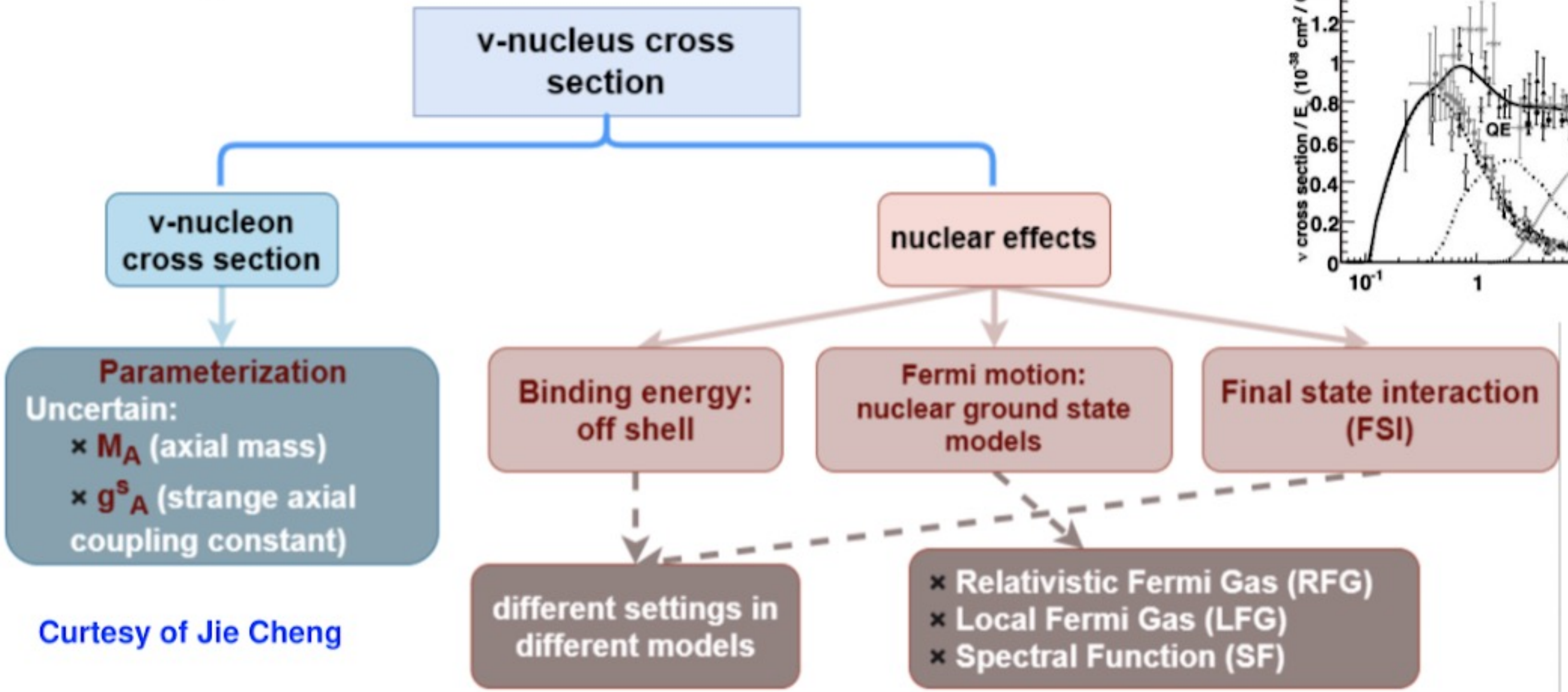


(b) $\nu_e/\bar{\nu}_e$ identification

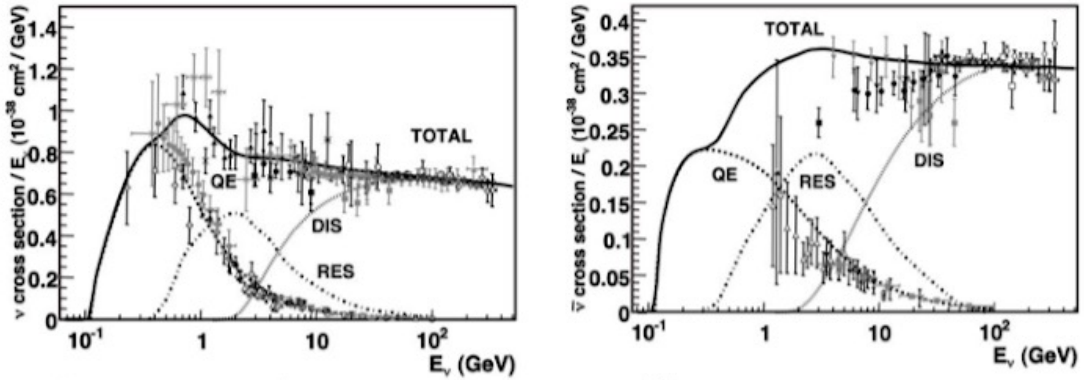
INTERACTION MODELS

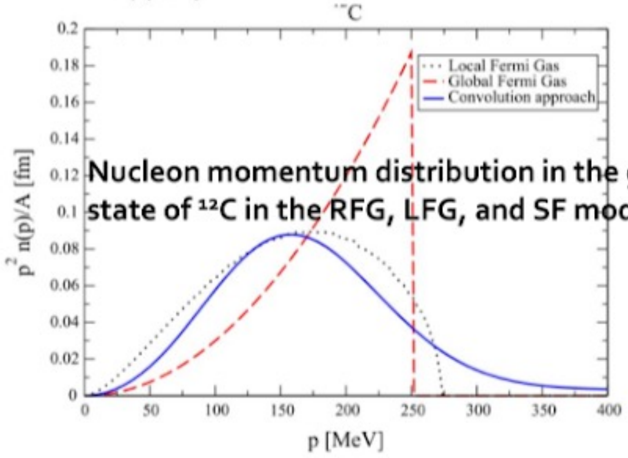
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012)

Brief summary of GeV neutrino interaction models



Curtesy of Jie Cheng





Nucleon momentum distribution in the ground state of ^{12}C in the RFG, LFG, and SF models.

- GeV neutrino interaction is model dependent! Existing generators at JUNO:
  - GENIE/NuWro/GiBUU
  - NEUT incorporation in progress
- We are working on the latest versions of the generators, within the Gev ν-A high-eNergY MEDium Effect (GANYMEDE) working group

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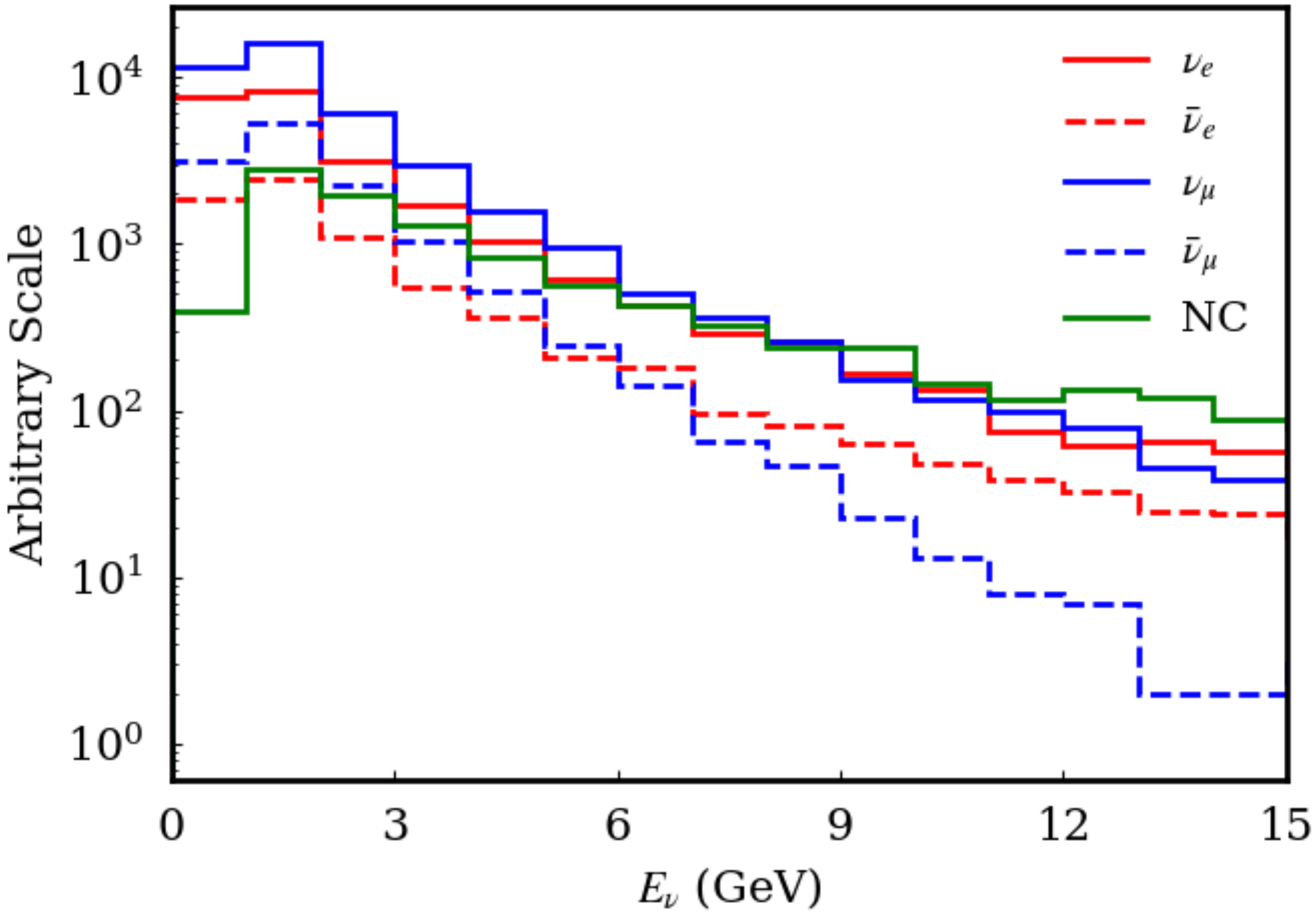
ATMOSPHERIC NEUTRINOS SPECTRUM



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5 knowns:

- ✓ $\Delta m^2_{21} \sim 7.5 \times 10^{-5} \text{eV}^2$
- ✓ $|\Delta m^2_{31}| \sim 2.5 \times 10^{-3} \text{eV}^2$
- ✓ $\sin^2 \theta_{12} \sim 0.3$
- ✓ $\sin^2 \theta_{23} \sim 0.5$
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All known with better than 5% precision

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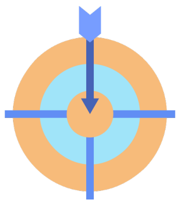
JUNO will contribute to both the precision and discovery frontiers



Precision measurement of three parameters: Δm^2_{21}, Δm^2_{31}, and $\sin^2 \theta_{12}$

Mass ordering determination

NEUTRINO SOURCES IN JUNO

Reactor $\bar{\nu}_e$ | Atmospheric $\nu/\bar{\nu}$ | Solar ν_e | Supernovae | Geo-neutrinos

Source	Expected rate
Reactor	~ 60 / day
SN burst	~ 7300 @ 10 kpc in few s
DSNB	~ 2-4 / year
Solar (^{8}B)	O(100) / day
Atmospheric	~ O(100) /year
Geo-neutrinos	~ 400 / year

Energy range